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MOISTURE FLOW THROUGH POROUS BUILDING MATERIALS

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MOISTURE FLOW THROUGH POROUS BUILDING MATERIALS

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SUMMARY

Moisture problems in building technology may be considered as analogous to the strength design and one may distinguish the following items:

(i) moisture loads - the environment description

(ii) moisture flow phenomena - the calculational methods

(iii) criteria - the allowed level of moisture content with regard to frost durability, deformations, heat losses etc.

(iv) designing - calculated moisture content under specified environmental conditions is compared with the criteria.

This report concerns moisture flow phenomena in broad, i.e. the model for calculations discussed here is based upon the detailed review of the moisture flow phenomena as well as the measuring techniques for the material properties inclusive the similitude requirements for the tested materials.

The apparent moisture transport may be caused by a number of different movements and cross-effects. Moisture may be transferred either as vapour or as liquid with a continuous phase exchange. With exception of extreme cases condensation as well as evaporation of water in pores take place continuously. The phase exchange is strongly temperature dependent, i.e. a gradient of the temperature may easily cause significant moisture content differences.

The model for calculations discussed here, contains two parts, one regarding moisture transport due to a gradient of moisture content, the other regarding moisture transport due to temperature gradient. Ratio between moisture transported in different phases (liquid/vapour) is not discussed in the model but assumed as defined by the natural conditions of the flow. The question about the uniqueness in the material properties expressed as functions of moisture content becomes extremely important.

Calculations seldom regard conditions similar to these where the material

properties were determined, one has to be able to predict how the material characteristics will be changed.

One knows quite a lot about the hysteresis in relation between moisture potential and moisture content at drying or wetting respective, one used, however, to omit the time effect as the dependence is determined in equilibrium state.

To explain it, the effect of air on the moisture flow must be recognized (Vachaud, 1972), and the following air effects analysed:

(i) air entrapment in the water field

(ii) air outflow due to water movement contributes to the flow resistance

(iii) to fill with water the space occupied by the entrapped air, either some time, or certain force are necessary, in both cases depending on the pore size.

Air may be dissolved in water but it takes different time in various pores. Air with the room temperature and atmosphere pressure is dissolved during a few seconds if the air bubble had diameter 10^{-5} m but a few months is required for an air bubble of 10^{-3} m.

Two different ranges divided by a knick point may be distinguished in a free water intake process. The upper range is ascribed to the air entrapment effects, i.e. moisture content in this range may be rised only when air escapes from the pores. These redistribution of moisture is called secondary flow mechanisms to contradict the primary flow mechanisms i.e. capillary forces dominating in the first stage of water intake processes.

The moisture content at the knick point of water intake is variable and depends amongst other on the moisture content of the beginning of the inflow.

In order to obtain a reproducable property, a new concept of capillary saturation was introduced. It corresponds to the highest possible knick point at the free water intake test. Practically it is determined on an absolutely dry specimen with all vertical sides insulated (to get one-dimen-

sional flow of water and air) placed in water up to 5 % of the height.

This moisture content describes in a way the end of "natural" water intake at the short time test. Wetting above this moisture content is also "natural" but based on another time scale, long time effects. Above the capillary saturation the similitude requirements (Bomberg, 1972) are not valid. To keep them valid one may divide the water intake process in two regions and use the following boundary conditions:

$$\text{for} \quad w < w_c \qquad w = w(p)$$

$$\text{for} \quad w \geq w_c \qquad w = w_c + w_a$$

where

p = capillary suction
w_c = moisture content at the capillary saturation
w_a = moisture content rise associated with the air escape and moisture redistribution processes.

Moreover a new concept of degree of actual saturation was introduced. It is a ratio between the actual moisture content and the moisture content where wetting run was finished and the process of drying was started (e.g. end of the rain period).

The degree of actual saturation is used instead of moisture content for all drying runs started in this region where air entrapment significantly influences the moisture transport.

This range is limited by the capillary saturation on one side and the critical moisture content at drying on the other side.

The degree of actual saturation contains a part of description of the capillary hysteresis and improves uniqueness in correlation between different material properties with regard to moisture.

This is the most important question concerning the model for calculations. The Simplified Relative Suction (SRS) model is built upon moisture diffusivity being a multi-valued function of moisture content. For drying pro-

cesses a correction factor based on the actual degree of saturation is introduced in the region between the capillary saturation and the critical moisture content at drying.

For wetting two different diffusivity curves are used, one for quick, the other for slow processes.

Material properties necessary for the calculations contain two items determined for the whole moisture content range:

1 moisture retention curve i.e. suction vs moisture content or degree of actual saturation

2 moisture diffusivity as a function of moisture content or degree of actual saturation.

The above characteristics contain several others e.g. sorption isotherm produce a piece of moisture retention curve, dry-cup vapour permeability is recalculated to one point on the moisture diffusivity curve etc. It is easy to recalculate different test results to these two basic material properties and opposite if so is useful. The principal difference between these two material properties and the old "simple" properties like: water absorption coefficient, water penetration coefficient, vapour permeability etc. is application to a general model for calculations. In Chapter 6 was shown that these material properties may be used for calculations of water intake (ground water, rain), drying, drying rate, condensation inside a porous material e.g. roof due to vapour transport from the ambient air, drying and wetting of the structures in sequences e.g. walls exposed to driving rains and following periods of drying.

One can calculate moisture flow through multilayered structures e.g. plastered or coated wall water exchange between clay-bricks and mortar during the brick-laying etc. if one knows material properties for all the layers in the structure.

There are some possibilities for predicting shrinkage and other deformations due to calculated moisture changes if knowing some other material properties.

Chapter 7 discuss the material testing as well as material description with regard to moisture properties. To use only density of the material is clearly insufficient. As the absolute minimum the following material properties should be required:

1. capillary saturation

2. absolute saturation

3. density of the dry material

4. dry-cup vapour permeability i.e. between 0 and 50 % RH

5. equilibrium moisture content at 50 % RH.

The above material properties together with the similitude requirements may be used for an evaluation of the moisture retention and diffusivity curves and judgement if a tested material is similar enough to permit use of the same set of material characteristics. Chapter 7 also shows a few examples of the experimentally determined material properties.

Finally, it may be claimed that SRS-model even simplified with regards to air transport, moistning hysteresis, capillary hysteresis during absorption etc. produces relatively good results (compare Chap. 6) and allows some calculations which have not been carried out before.

SAMMANFATTNING

Byggnadstekniska fuktproblem kan betraktas i full analogi till hållfasthetsteknisk dimensionering. Härvid urskiljes följande problem:

fuktkällor - man beskriver miljö,
fuktmekanik - man skapar beräkningsmetoder,
tillåtna fukttillstånd - man skapar kriteria med hänsyn till materialens fuktkänslighet
dimensionering - man beräknar fukttillståndet under angivna klimatiska villkor och jämför med tillåtna fukthalter.

Följande rapport behandlar fuktmekaniken i vid mening, dvs att med kännedom om de tämligen komplicerade fysiska förloppen leda fram till en jämförelsevis enkel och fullständig beräkningsmodell samt presentera mätmetoder för att bestämma alla nödvändiga materialdata så att likformighetsvillkoren är uppfyllda.

Den fukttransport som i verkligheten observeras är resultat av olika sorters strömningar och korsande effekter. Fukt tranporteras dels som ånga dels som vätska men med ett ständigt utbyte mellan dessa faser. Med undantag för extrema förhållanden pågår alltid kondensation och avdunstning inom porerna. I sin tur är detta ombyte kraftigt beroende av temperaturen, vilket innebär att en temperaturgradient lätt kan förorsaka stora fukthaltsskillnader.

Den beräkningsmodell som används här innehåller därför två delar, den ena avser fukttransport p g a fukthaltsgradient, den andra fukttransport p g a temperaturgradient. I beräkningsmodellen skiljs inte mellan transport i olika faser (vätska resp ånga) utan förhållandena mellan dessa anses vara betingade av "naturliga" villkor. Frågan om entydigheten i sambanden mellan fukthalt och olika materialkaraktäristika kommer därför att få avgörande betydelse.

Eftersom beräkningarna sällan avser samma förhållanden som vid bestämningen av materialdata, måste man kunna förutsäga hur materialdata ändras.

Man känner till en del hysteresisfenomen, dvs ändring av sambanden mel-

lan fukthalt och fuktpotential vid uppfuktnings- resp uttorkningsförlopp, men man brukar försumma tidens inverkan på dessa fenomen, eftersom sambandet bestäms vid jämviktsläget.

För att förklara detta diskuteras luftfasens inverkan på fukttransporten (Vachaud, 1972). Vätsketransporten är beroende av luftfasen på tre olika sätt:

1 Mindre eller större luftblåsor innestängs av vattnet.

2 Även luften utövar ett strömningsmotstånd.

3 För att vattenfylla det stängda utrymme som luftblåsorna utgör, behövs det antingen en viss tid eller viss kraft, i båda fallen beroende av porstorleken.

Luft kan lösa sig i vatten men det behövs mycket olika tid för denna upplösning vid olika förhållanden. Om ytterluften har atmosfärtryck, behövs det vid rumstemperatur endast några få sekunder för att upplösa en luftbubbla med diametern 10^{-5} m men några månader vid diametern 10^{-3} m.

Om man bestämmer vattenuppsugningen från en fri vattenyta får man en knyck på uppsugningskurvan mellan två olika uppsugningsområden. Denna punkt representerar den gräns där luftblockaden avgör den fortsatta vattenuppsugningen. Ovanför denna gräns har man huvudsakligen en fukthaltsökning p g a omfördelning av fukten, och vi kallar detta sekundära transportmekanismer.

Den fukthalt som erhålls vid knyckpunkten kan dock variera beroende på försöksutförande, t ex begynnelsefukthalt.

För att erhålla en reproducerbar egenskap införes ett nytt begrepp - "kapillär mättnadsfukthalt" - som svarar mot den högsta av alla möjliga knyckpunkter vid ett vattenuppsugningsförsök. Praktiskt bestämmer man kapillär mättnadsfukthalt genom uppfuktningsförsök med en i början torr provbit. Provbiten har isolerade sidor (för att erhålla endimensionell luft- och vattenströmning), och den placeras i vatten till max 5 % av höjden.

Denna fukthalt betecknar därför på sätt och vis slutet för "naturlig" fuktupptagningsförmåga vid korttidsförsök. Uppfuktning ovanför denna fukthalt är också "naturlig" men baseras på en annan tidsskala, långtidseffekter. Ovanför den kapillärmättnadsfukthalten gäller därför ej de likformighetsvillkor som annars kan tillämpas (Bomberg, 1972).

För att behålla giltigheten av likformighetsvillkoren kommer randvillkor för uppsugningsförlopp att uttryckas i följande formler:

$$\text{för } w < w_c \qquad w = w(p)$$

$$\text{för } w \geq w_c \qquad w = w_c + w_a$$

där p = kapillärt sug

w_c = kapillär mättningsfukthalt

w_a = fukttillskott p g a luftutgång ur vätskefält.

Dessutom införes ett nytt begrepp verklig mättningsgrad som utgår från kvoten mellan den verkliga fukthalten och den fukthalt där uppfuktningen slutades och förloppet vände till en uttorkning (t ex slut av regnperiod).

Verklig mättnadsgrad används istället för fukthalt för alla torkningsförlopp som påbörjas i område där luftblockaden väsentligt inverkar på fukttransport.

Kapillär mättnadsfukthalt och kritisk fukthalt vid uttorkningen utgör en grov uppskattning av gränserna för detta område, där luftfasens inverkan på vätsketransport är störst. Den verkliga mättningsgraden innefattar en del av beskrivningen av den kapillära hysteresiseffekten och därmed förbättras entydigheten i sambanden mellan olika fuktegenskaper hos materialet ifråga.

Detta är det väsentligaste momentet hos beräkningsmodellen ifråga. Simplified Relative Suction modellen innebär, att fuktdiffusiviteten är en flerfaldig funktion av fukthalten. För uttorkningsförlopp införs en på den verkliga mättningsgraden baserad korrigeringsfaktor som tillämpas i området mellan kapillär mättnadsgrad och kritisk fukthalt vid uttorkningen.

För uppfuktningsförlopp tillämpas två alternativa fuktdiffusivitetskurvor, en för snabba och en annan för långsamma förlopp.

Materialdata nödvändiga för beräkningar består av två samband:

1 vattenkvarhållningskurva, (water retention curve), dvs sambandet mellan fukthalten och fuktpotentialen (suction - på svenska kallad sug) för hela fukthaltsområdet.

2 fuktdiffusivitetskurva, dvs samband mellan fukthalten och en transportkoefficient bestämd också för hela fukthaltsområdet.

Ovanstående materialkarakteristikor innefattar en rad andra materialdata t ex utgör sorptions-isotermen en del av vattenkvarhållningskurvan och ångpermeabiliteten en punkt på fuktdiffusivitetskurvan.

Det är lätt att räkna om olika provningsresultat till dessa två grundläggande karakteristikor och tvärtom om så behövs. Med kännedom om dessa två huvudkarakteristikor och med hjälp av SRS-modellen kan man beräkna fukthalt och fukthaltsfördelning under praktiskt taget alla möjliga tillämpningar. I kap 6 redovisas beräkningar av vattenuppsugning (grundvatten, regn), uttorkning, uttorkningshastighet, kondensation inom ett poröst material i t ex takkonstruktion p g a uppfuktning från luften, och uppfuktning med efterföljande uttorkningsperioden. Sådana beräkningar var icke möjliga så länge man arbetade med de gamla "enkla" fuktkarakteristikorna t ex vattenuppsugning, ångpermeabilitet osv.

Man kan även beräkna sammansatta konstruktioner, t ex putsad, vägg eller speciella problem, t ex kapillärvatten i mark invid grunder, vattentransport från bruk till sten under murning mm. Detta förutsätter dock att man har fuktdata för alla skikt i konstruktionen.

Det finns vissa möjligheter att med hjälp av några enkla provningar och beräknade fukthaltsvariationer förutsäga fuktbetingade rörelser, krympning m m.

I kapitel 7 diskuteras materialprovning och i synnerhet materialbeskivning i samband med fuktttekniska försök. Att beskriva material enbart med hjälp av densitet är otillfredsställande. Som ett absolut minimum krävs bestämning av följande materialdata:

1 kapillär mättnadsfukthalt

2 absolut mättnadsfukthalt

3 densitet hos torrt material

4 ångpermeabilitet enligt dry-cup metoden, dvs mellan 0 och 50 % relativ ånghalt

5 jämviktsfukthalt vid 50 % relativ ånghalt.

Ovannämnda materialdata kan med hjälp av likformighetsvillkor användas för att uppskatta vattenkvarhållningskurva och diffusivitetskurva och i synnerhet bedöma om provade material avviker från den materialbit vars data är kända. I kapitel 7 visas också några exempel på de bestämda materialegenskaperna.

Avslutningsvis kan framhållas att SRS-modellen ger tämligen goda resultat (se kap 6) trots att den är förenklad i några avseenden (lufttransport, fuktningshysteresis, kapillär hysteresis under uppfuktningen m m). Den tillåter vissa beräkningar som hittills ej varit möjliga.

LIST OF SYMBOLS

Concept	Symbol	Unit
coordinates	x,y,z,	m
length	l	m
height	h	m
thickness	d	m
radius	r	m
wetting angle	θ	1
area	A	m^2
volume	V	m^3
mass	m	kg
density (bulk density)	ρ	kg/m^3
time	t	s
velocity	v	m/s
acceleration of free fall	g	m/s^2
work, energy	E	J
force	F	N
free energy relative to a free pure water	Δf	J/kg
density of heat flow rate (heat flow per unit time and area)	q	W/m^2
temperature	T	K
thermal conductivity coefficient	λ	W/mK
heat capacity	C	J/K
specific heat	c	J/kg K
surface coefficient of heat transfer	α	W/m^2 K
gas constant for water vapour	R_v	J/kg K
moisture content	w	kg/m^3
moisture content at a characteristic point (in general)	w_n	kg/m^3
critical moisture content	w_{cr}	kg/m^3
moisture content at the absolute saturation	w_s	kg/m^3
moisture content at the capillary saturation	w_c	kg/m^3
moisture content at the bubbling point	w_b	kg/m^3
moisture content at the start point of the actual drying run	w_{os}	kg/m^3

degree of saturation $S = \frac{w}{w_s}$	S	1
degree of actual saturation $S_{A,d} = \frac{w}{w_{os}}$, $S_{A,w} = \frac{w}{w_c}$	S_A	1
air content	a	kg/m^3
suction (total suction)	p	N/m^2
capillary suction	p_c	N/m^2
backing suction of the material	p_o	N/m^2
bubbling pressure (= suction)	p_b	N/m^2
relative suction, $P = \frac{p}{p_n}$	P	1
total pressure	p_{tot}	N/m^2
partial pressure of water vapour	p_v	N/m^2
partial pressure of air	p_a	N/m^2
concentration of water vapour (mass concentration of water vapour)	c	kg/m^3
relative humidity (relative vapour concentration)	ϕ	1
vapour conductivity coefficient related to a vapour concentration gradient	δ	m^2/s
vapour differential capacity $\xi = \frac{dw}{d\phi}$	ξ	kg/m^3
vapour diffusivity related to a moisture content gradient $D_v = \frac{\delta c_s}{\xi}$	D_v	m^2/s
liquid diffusivity related to a moisture content gradient	D_l	m^2/s
moisture diffusivity, (isothermal moisture diffusivity related to a moisture content gradient)	D	m^2/s
thermal moisture diffusivity, (moisture diffusivity related at temperature gradient)	D_T	kg/m s K
moisture conductivity coefficient	k	s (= kg m/Ns)
differential moisture capacity $e = \frac{dw}{dp}$, $e = \frac{k}{D}$	e	s^2/m^2
intrinsic permeability coefficient $\kappa = k \cdot \frac{\eta}{\rho}$	κ	m^2
dynamic viscosity	η	kg/m s

mass flow rate	Q_m	kg/s
density of mass flow rate	q_m	kg/m^2 s
density of vapour flow rate	$q_{m,v}$	kg/m^2 s
density of liquid flow rate	$q_{m,l}$	kg/m^2 s
surface coefficient of vapour transfer	β	s/m
surface tension of water	σ	N/m

Notations infrequently used in the report are not listed above.

SUBSCRIPTS

A = actual value
a = related to air
b = related to bubbling point
c = related to capillary
cr = critical
ct = convective
d = related to drying
e = external, outside or end of calculations
ef = effective
f = final state
g = related to a field of gravity
i = internal, inside or beginning of calculations
j = related to moisture potential
kn = related to knick point during drying
l = related to liquid phase
m = related to mass, mass flow etc.
n = calculational, related to a characteristic point
o = initial state, special case
os = initially saturated (partly)
p = related to pressure
s = saturated
u = osmotic, related to salt-contents gradient
v = related to vapour phase, related to WVT [x)] region
vs = related to saturated vapour
vol = volumetric
wt = related to wetting
x,y = related to coordinates in a plane
z = related to the third coordinate

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x) term "WVT" = water vapour transmission is being prefered to vapour diffusion.

FOREWORD

The following report is based on the research concerning liquid phase movement in porous materials, sponsored by the Swedish National Building Research Council and carried out at the Division of Building Technology of the Lund Institute of Technology.

The knowledge of how to predict the moisture content of building materials during their service life seems to be acutely required and may contribute to significant economic savings by enabling:

- a better choice of material for a particular application of performance

- the design of structures with regard to moisture conditions.

The present state of knowledge and trends in moisture research within building technology are discussed in the publication of the National Swedish Building Research (Adamson et al., 1970).

The present stage of our knowledge of moisture transport in porous materials in discussed mainly in soil science publications.

The books: Soil Water (1972) and Methods of Soil Analysis (1965) indicate the scope of the research field.

Some research workers concerned with engineering applications may find it difficult to place our concepts in the full context of moisture movement research. A short general introduction is therefore presented to indicate how the basis for our calculational model is based on some concepts known in the field of soil science.

Chapters 2-4 discuss some general features of moisture transport, while Chapter 5 deals with a few specific problems connected with the calculational model. Chapter 6 deals with the application of the simplified version of this model.

I would like to express my gratitude to all those who assisted in this work.

First of all I would like to express my sincerest thanks to Professor Lars Erik Nevander, Head of the Department, who initiated this research. His advice and encouragement throughout the course of the investigation were a great help to me.

I am indebted to Professor Vagn Korsgaard and tekn. lic. Anker Nielsen at the Heat Insulation Laboratory of Danish Technical University for the use of the gamma radiation apparatus and for computer evaluation of measurements.

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I am thankful to all my colleagues at the Department for helpful discussions. I am also indebted to a number of research workers from the Americal Soil Science Society for valuable advice. I am particularly indebted to the research workers at the Carleton University, Ottawa, Canada and the Soil and Water Institute, Rehovot (Bet Dagan), Israel, for fruitful discussions.

Finally I wish to thank my colleagues at the Department for assistance with the measurements and calculations. I am particularly grateful to Mrs. Lilian Johansson who prepared the figures for the report and Mrs. Mary Lindqvist who typed the manuscript.

Lund, December, 1973

Mårk Bomberg

1 INTRODUCTION

Moisture movement may be initiated by diverse forces: difference in pressure of the pore-water, gravity, osmotic, external air- and freezing pressures (not discussed in the following report), vapour concentration difference, temperature gradient etc.. Moisture may be transported in vapour or liquid phase, as well as in both phases. The flow of these phases may be either parallel, or in series; either in the same direction, or in opposite directions, as for instance in the saturated moisture flow induced by a temperature gradient. Each moisture flow creates a temperature gradient and vice versa, as change of phase is associated with a significant quantity of heat.

All the moisture flows are, however, strictly interconnected as the capillary moisture potential for water in liquid and vapour phase is the same. For a normal calculation of moisture transport through a porous material, the following material properties should be known as a function of moisture content:

(a) Moisture potential.

(b) Moisture conductivity related to moisture potential.

(c) Moisture conductivity related to temperature gradient.

If only the isothermal moisture transport is considered, properties (a) and (b) should be known. The following difficulties in the determination of these properties should be noted:

(i) Both moisture potential and conductivity coefficient may differ by about 10^4 - 10^5 between low and high degree of moisture saturation.

(ii) Moisture potential may produce several functions of moisture content if the hysteretic background differs from test to test.

(iii) Moisture diffusivity (contains both conductivity and differential moisture capacity as explained later) may also show a hysteretic behaviour.

Fig. 1 A shows moisture diffusivity coefficient of the aerated concrete calculated by Nielsen (1973) from the one-side drying experiments where moisture content distribution were determined by means of a gamma attenuation technique. Fig. 1 B shows results from the same calculations but related to a 10 mm layer in the middle of the specimen.

The character of the diffusivity curves is varied. Instead of ω-formed curves in the Fig. 1 A, the v-formed vurves are obtained as shown in Fig. 1 B.

Another example of discrepancies in the results of tests performed on different specimens under the same testing conditions is shown by Butijn & Wesseling (1959). Some results of their tests are shown in Table 1-1.

Table 1-1. Capillary conductivity in cm/day for the Dune sand calculated according to the Gardner's method and the square root of time (Crank's method), for suction step from 3×10^2 to 5×10^2 N/m^2.

Number of the specimen	Desorption		Sorption	
	Crank	Gardner	Gardner	Crank
16	0,2040	0,1630	0,174	0,217
17	0,0032	0,0027	16,4	14,0
18	0,0643	0,0560	0,0022	0,0023
19	0,0525	0,0444	0,00020	0,00021
20	-	-	0,00046	0,00110
21	-	-	0,000068	0,000100
22	-	-	0,0166	0,0180
23	-	-	0,00043	0,00090

The difficulties in determining properties of materials tend to influence the way of calculations. The models for moisture flow calculations either become very detailed, complex and unpractical for engineering applications (cf. Lykov, 1964, 1956) or simple and useful for given practical purpose but limited to a set of specific boundary conditions (cf. Soil Water, 1972).

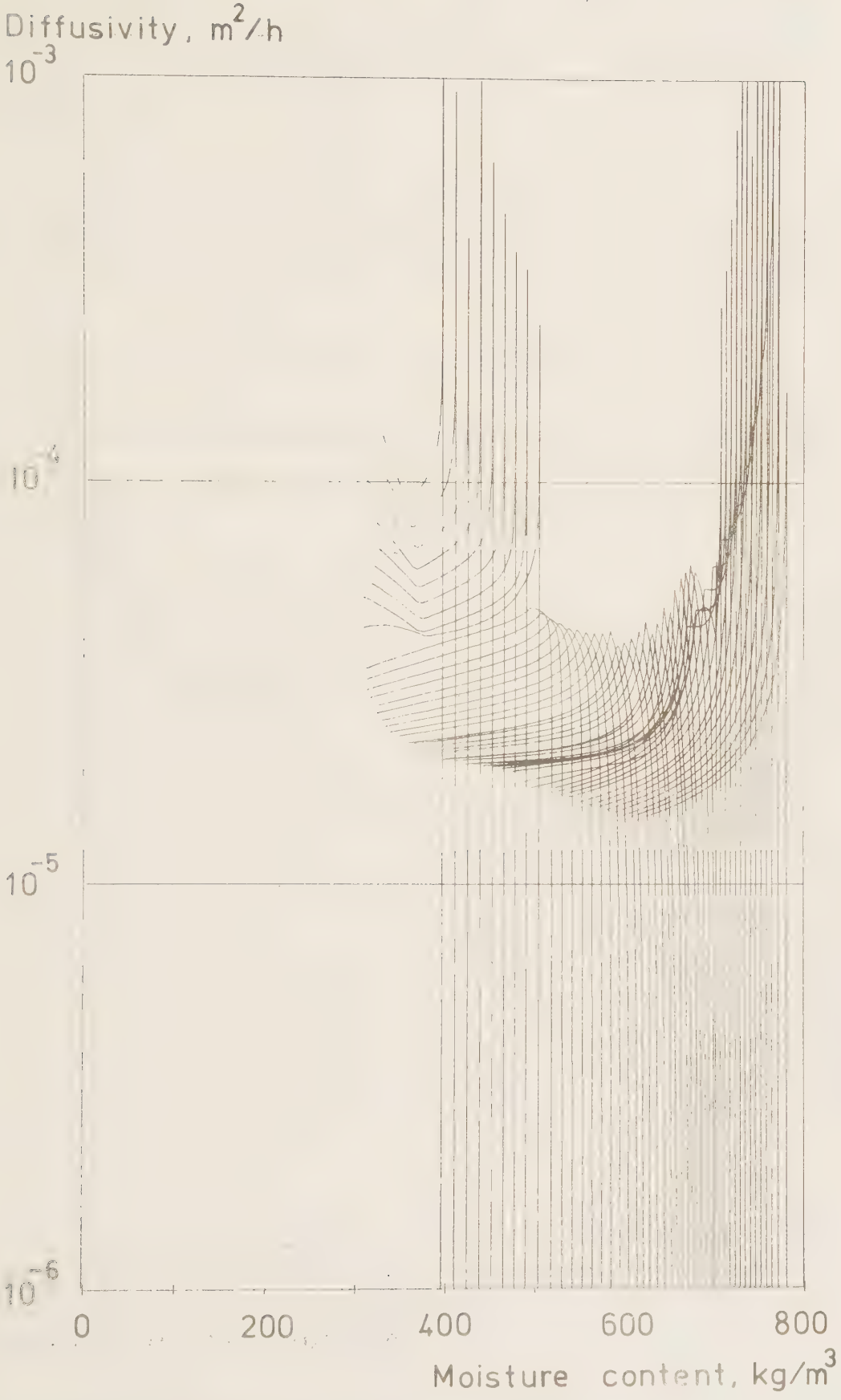


Fig. 1A. Diffusivity coefficient of aerated concrete, computed by Nielsen (1974) on the same specimen with a method described by Mahler (1958).

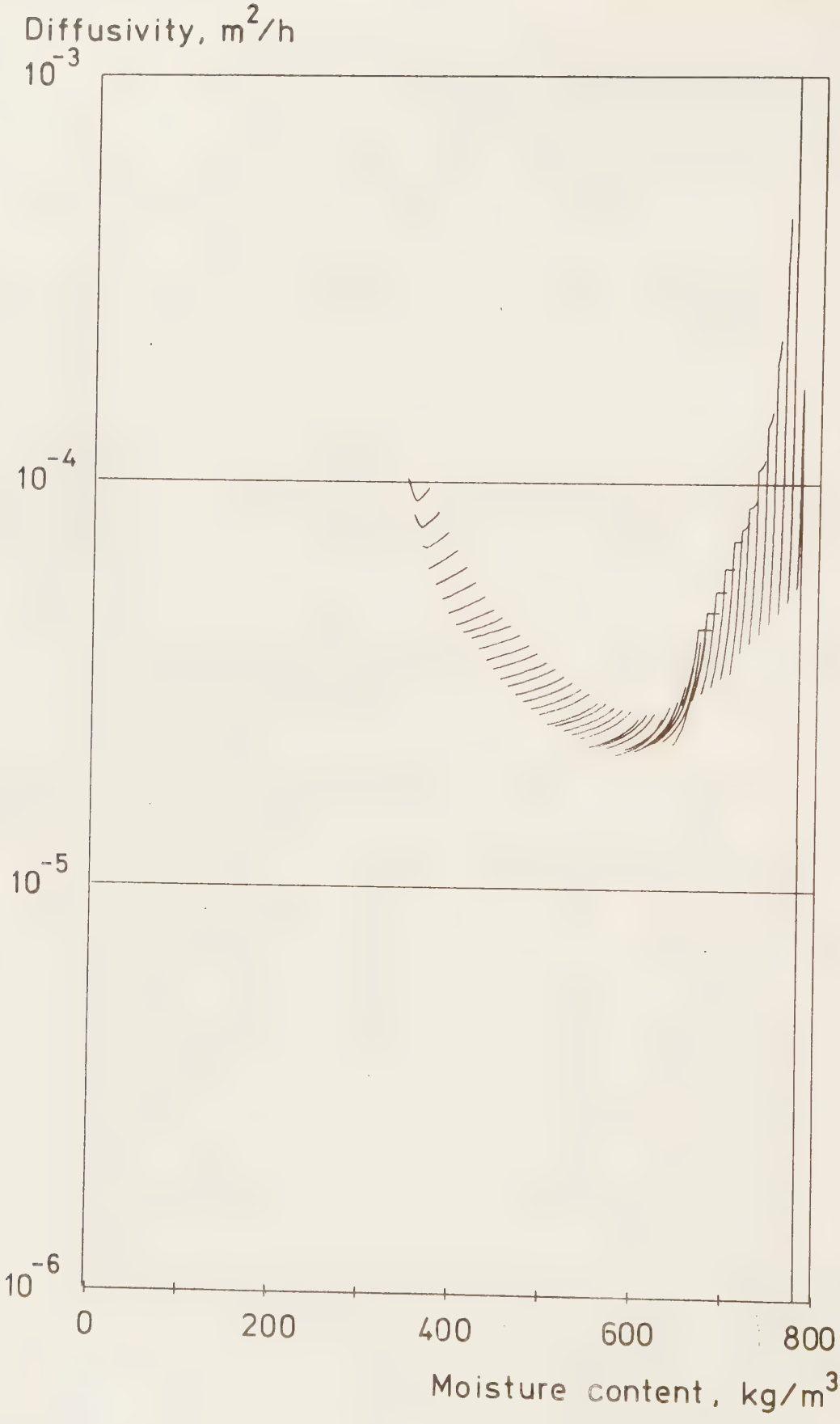


Fig. 1B. Diffusivity coefficient of aerated concrete as shown in Fig. 1A but calculated for the layer between 15 and 25 mm from the closed side. After Nielsen (1974).

The aim of this work is to produce a simple and approximate model for moisture transfer through porous materials exposed to either air (drying or wetting by vapour diffusion) or liquid water e.g. rain of a given intensity.

The analysis of unsaturated water flow showed that the effects of air entrapment in liquid field may not be omitted. The liquid water flow is interconnected with the air phase in the pore system. It has two effects:

(a) Some air bubbles are entrapped in the liquid fields,

(b) Air must be allowed to escape if water is to fill all the capillaries.

Both two effects are strictly time-dependent.

Time necessary for air bubbles to dissolve in water is dependent upon the bubble radius. A replacement of air bubbles with water which occurs without any change in the moisture potential may introduce a time effect into the moisture retention curve, a relation hitherto assumed to be time-independent. Another problem where time effect is encountered, in a generally assumed time-independent phenomenon, is shown in Fig. 2.

Fig. 2 describes tests where water was filtered through a specimen placed between two porous plates. It was circulated in a closed circuit between two levels, and kept steady during the whole test. Tests were performed twice: firstly, with water pressure lower than atmospheric, about 6×10^3 N/m^2 and absolutely saturated specimen at the beginning, secondly, with water pressure higher than atmospheric, about 1.6×10^4 N/m^2 and moisture content as reached in the previous test. Pressure gradient was similar in both cases.

It may be seen in Fig. 2 that the steady state (steady level of hydraulic conductivity) is achieved after about a month of the flow with the water pressure higher than the atmospheric one i.e. saturated water flow.

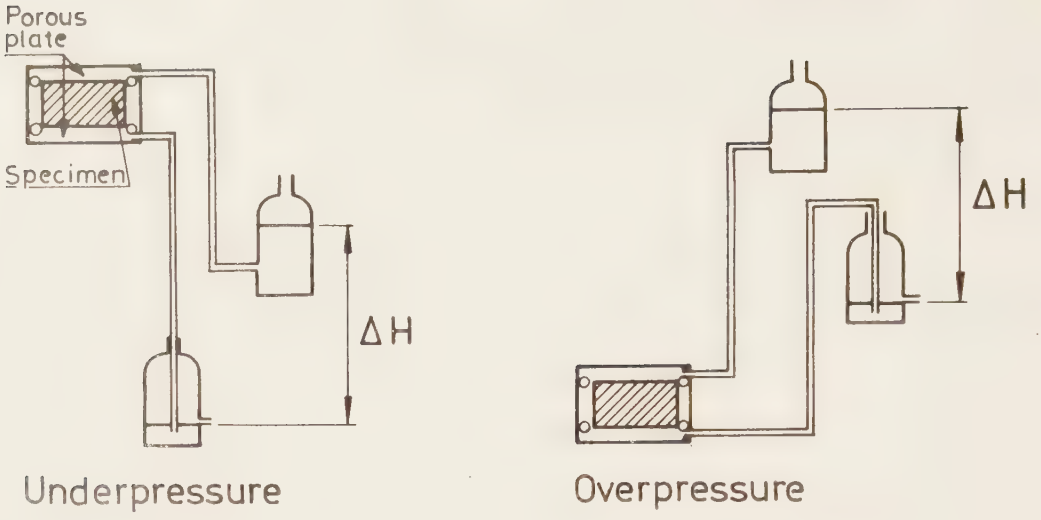


Fig. 2 A. Conditions of the tests. The clay-brick specimen had diameter ϕ 64 mm and thickness about 20 mm.

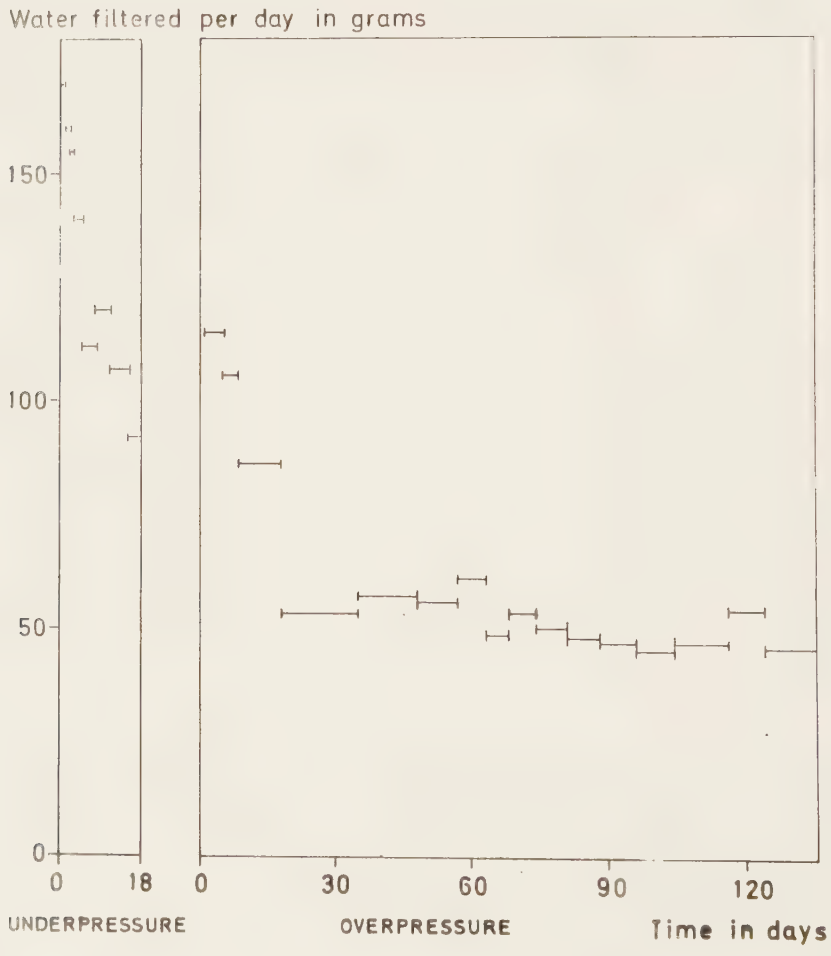


Fig. 2 B. Water flux as influenced by the time-dependent effects in the steady state conditions.

The steady state was not achieved in 18 days of the unsaturated water flow. It may be noted that in this time conductivity coefficient showed values much higher than the probable maximum, perhaps because the specimen was saturated under vacuum prior to this series of tests.

The above experiment illustrates influence of air on the moisture transport (see also Chapter 13 of Bomberg, 1971). This subject was investigated by Vachaud (1972), who states:

"We conclude that the air pressure must be taken into account when determining the soil water suction, and we suggest that the flow equations must be written in terms of two phase immiscible fluid flow."

This line of approach is developed by others, for instance, Morel-Seytoux (1971, 1972).

A different approach is used in this report. Air pressure is introduced directly into the capillary suction producing a new concept: corrected capillary suction. The corrected capillary suction differs from the apparent capillary suction when a free air outflow is obstructed i.e. if moisture content is higher than a bubbling point.

Wetting and drying runs are treated in a different way in the model developed here, called the simplified relative suction (SRS) model.

All the wetting runs are considered as if they were started from the absolute dryness. Wetting process continues until a capillary saturation is achieved, when the corrected capillary suction becomes equal to zero. Higher moisture content may be achieved because of the following factors:

(a) A time-dependent rise of moisture content at the boundary surface as an effect of air outflow.

(b) Potentials other than capillary suction acting on the system.

For drying runs, different density of drying rate may be introduced for the same moisture content, as a function of the conditions when the drying run was started.

Starting moisture content is introduced into each drying run calculation through a new concept, introduced in this report, namely degree of actual saturation.

Moisture diffusivity, assumed to be a function of the degree of actual saturation, is dependent on both the actual moisture content and this moisture content when the wetting run turned into the drying run.

The thermally driven flows are described in a separate part of the moisture flow equation.

The analysis shows that the temperature gradient influence may be attributed to the vapour phase movement. Although the movement contains condensation and evaporation in series, Fick's law seems to be applicable if the vapour conductivity coefficient describes the WVT (water vapour transmission) not a vapour diffusion without a phase exchange.

Finally the SRS-model consisting of two parts: isothermal and temperature gradients, is discussed in Chapter 5.

The applications of this model and the testing of material properties are discussed in Chapter 6 and 7, respectively.

2 ISOTHERMAL CONDITIONS

2.1 Moisture equilibria under isothermal conditions.

A piece of a dry, porous material placed in a climatic chamber where both temperature and relative humidity are constant absorbs water and changes its weight.

In course of time the weight change decreases until it becomes negligible and the specimen reaches an equilibrium state. The time required to reach this approximate equilibrium state depends on the pore structure of the tested material and a number of factors in the experimental arrangement such as dimensions of the specimen, relative humidity and temperature fluctuations. To reach the approximate equilibrium state a period of about 2-3 weeks is necessary when testing grained building materials, but in some cases, for instance larger dimensions or highly impermeable cellular plastics the tests must last for a few months. This time may be shortened by application of a temperature gradient.

Moisture equilibria obtained by a vapour exchange between the specimen and the ambient air are usually reported in the form of sorption curves, where the relative humidity of air is plotted against the moisture content of the material.

Moisture equilibria obtained either during wetting (absorption) or drying (desorption) are quite different, as shown in Fig. 3.

The character of a sorption curve is also influenced by the following factors: moisture content at the beginning of tests (particularly during a desorption process) and variations of the temperature or vapour concentration in the ambient air.

Weight changes of wood specimens under varied test conditions are illustrated in Fig. 4. Both vapour concentration and temperature in the ambient air were changed during the absorption process. The measured values of relative humidity are also shown in Fig. 4 against the recalculated relative humidity of air (which could occur if the air temperature were constant and equal to $T = 296$ K).

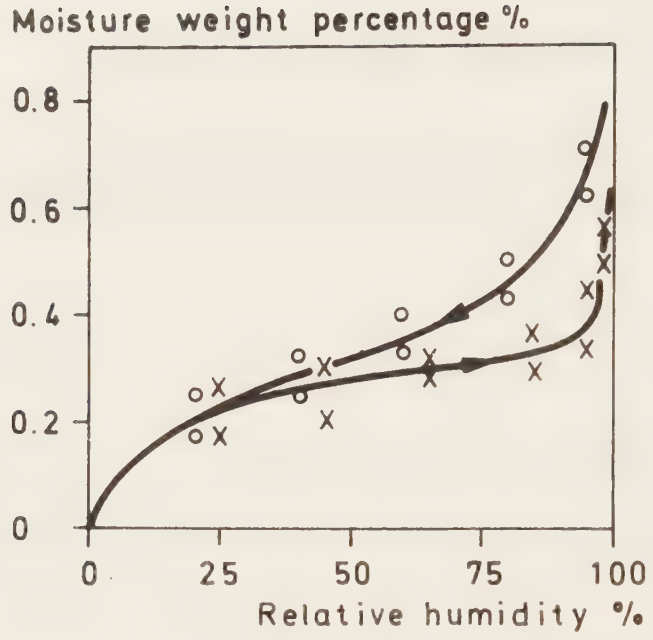


Fig. 3. Sorption isotherms for clay-brick with density about 1860 kg/m^3, open porosity 0,31 m^3/m^3. After Ahlgren (1972).

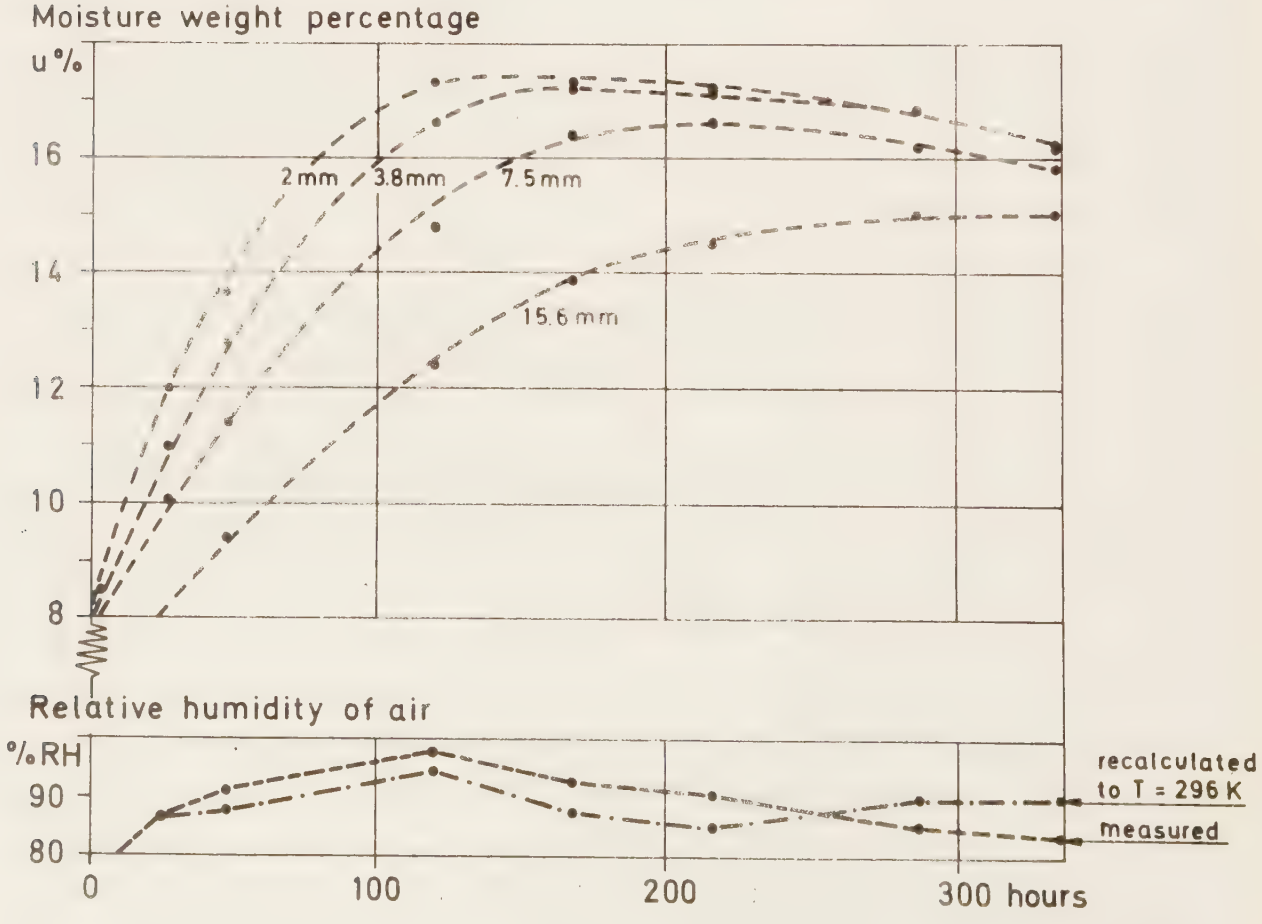


Fig. 4. Weight change of wood (pine) during absorption started from the equilibrium at 52 % R.H.. After Nielsen (1968).

Both, the measured and recalculated relative humidities reached a clear maximum at about 120 hours.

It may be seen in Fig. 4 that specimens 2 mm thick followed changes in the relative humidity. Specimens having a thickness of 15,6 mm showed an increase in weight during the whole period (i.e. did not react on the alteration in the first period) and the medium-thick specimens of 3,8 mm and 7,5 mm showed maxima on seventh and ninth day, respectively.

Other tests performed by Nielsen (1968), showed under certain testing conditions, differences between moisture equilibria obtained with thin and thick specimens. Those differences were clearly visible in two cases:

a) The drying of the specimen was not completed, and the following wetting run was started not at the absolute dryness but at a certain moisture content.

b) If the temperature of the ambient air oscillated with a long cycle period (even though with a small amplitude).

It would appear therefore that only the utmost sorption curves should be tested. A drying run should be started at the full saturation (vacuum saturation) and a wetting run should be started at the absolute dryness.

Moreover, a practical limit for the sorption tests is placed at 95 or 98 % R.H., depending upon the experimental facilities.

Some authors, however, try to distinguish between moisture equilibria under and above 98 % RH. The first is called hygroscopic, the second capillary moisture. This has no physical meaning. The concept hygroscopic moisture indicates only that a certain experimental technique was used.

Until now, wetting of the specimen took place with water from the air, transported in a vapour phase. Moisture equilibria may also be determined by means of a liquid phase transport, for instance by placing a specimen in a direct contact with water. The thermodynamic potential of this water must be, however, constant and known.

This requirement may be fulfilled if the water is supplied from, for instance, a porous plate apparatus.

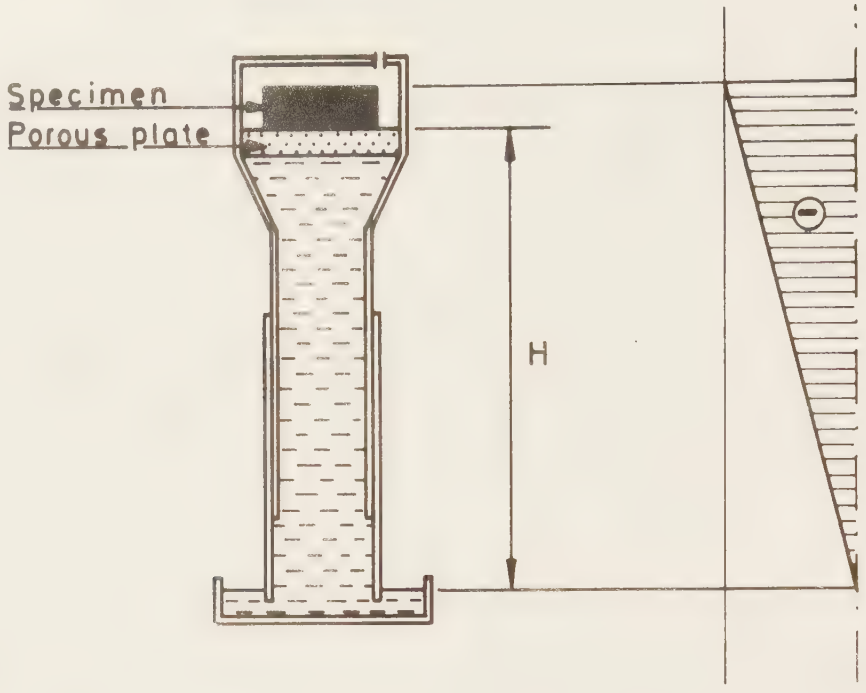


Fig. 5. The concept of porous plate (vacuum plate) apparatus. Water underpressure is also shown in the figure.

If a fully saturated specimen is placed on a porous plate in contact with water having a certain and constant underpressure, then a part of the water from the pores will leave the specimen. Water which remains in the specimen must have a certain energy level, at least sufficient to produce the same "tension" as water "suction" caused by the water underpressure. The terms "water tension" or "water suction" as used in soil science, are introduced below. For further definitions see Appendix A.

The equilibrium case, under isothermal conditions may be written as follows:

$$p_c = \rho R_v T \ln \phi \quad (1)$$

where:

p_c = capillary suction, N/m^2

R_v = gas constant for water vapour, J/kg K

T = temperature, K

ϕ = relative humidity in the air layer adjacent to the water surface

ρ = density of water, kg/m^3

The capillary suction is defined as a negative difference between the ambient air and the pore-water pressures. Tension is equal to a negative suction.

A condition necessary for work with the porous plate apparatus, as shown in Fig. 5, concerns the contact plane between the specimen and the porous plate. The water filling the capillary system of the specimen must come in contact with the water in the apparatus, otherwise no outflow from the specimen can take place. For this reason the use of the vacuum plate apparatus is limited by a bubbling pressure of the porous plate. The bubbling pressure indicates the pressure level, at which the air bubble can pass through a porous membrane covered with water films on both sides.

Water in the material may also be separated from the water in the apparatus due to a process of air separation from the water exposed to the vacuum. For this reason another apparatus was constructed providing wider range of the test conditions.

This apparatus, shown in Fig. 7, is called a pressure cell. Water in the apparatus has the atmospheric pressure but air in the chamber has an increased pressure, so that a pressure difference over the specimen causes a water outflow. The water outflow continues until the specimen reaches an equilibrium state.

A diagram showing moisture content in equilibrium with suction is called a moisture retention curve.

Suction is expressed in pressure units. It has been shown elsewhere (see: Brooks & Corey, 1964; Corey & Corey, 1967) that double logarithmic plot of moisture retention curves gives better approximation than a linear one. In this way a logarithm of suction is indirectly introduced, even the so-called pF-scale is now considered as obsolete.

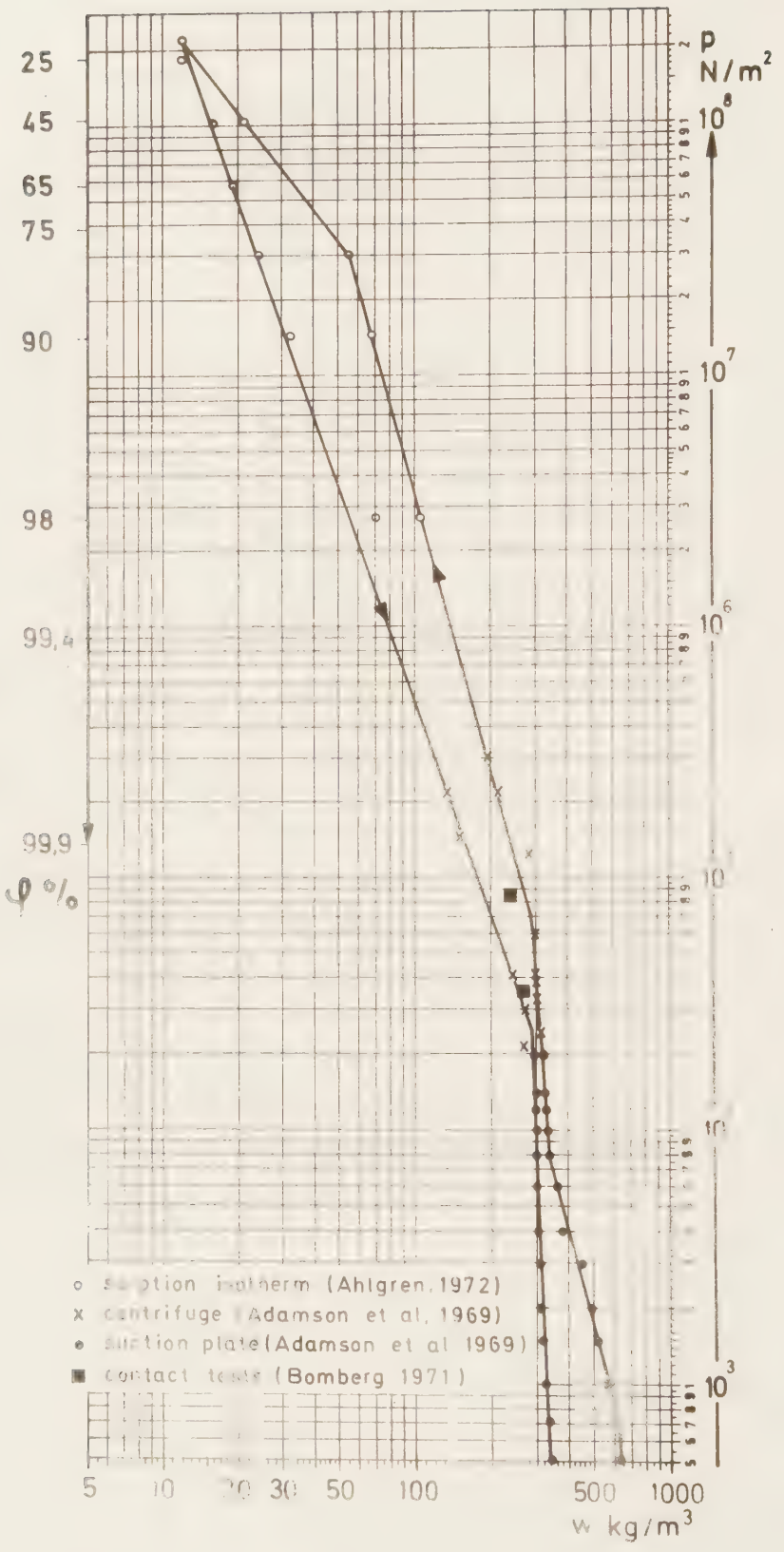


Fig. 6. Moisture retention curves for aerated concrete with density about 500 kg/m³ according to tests at the Lund Institute of Technology.

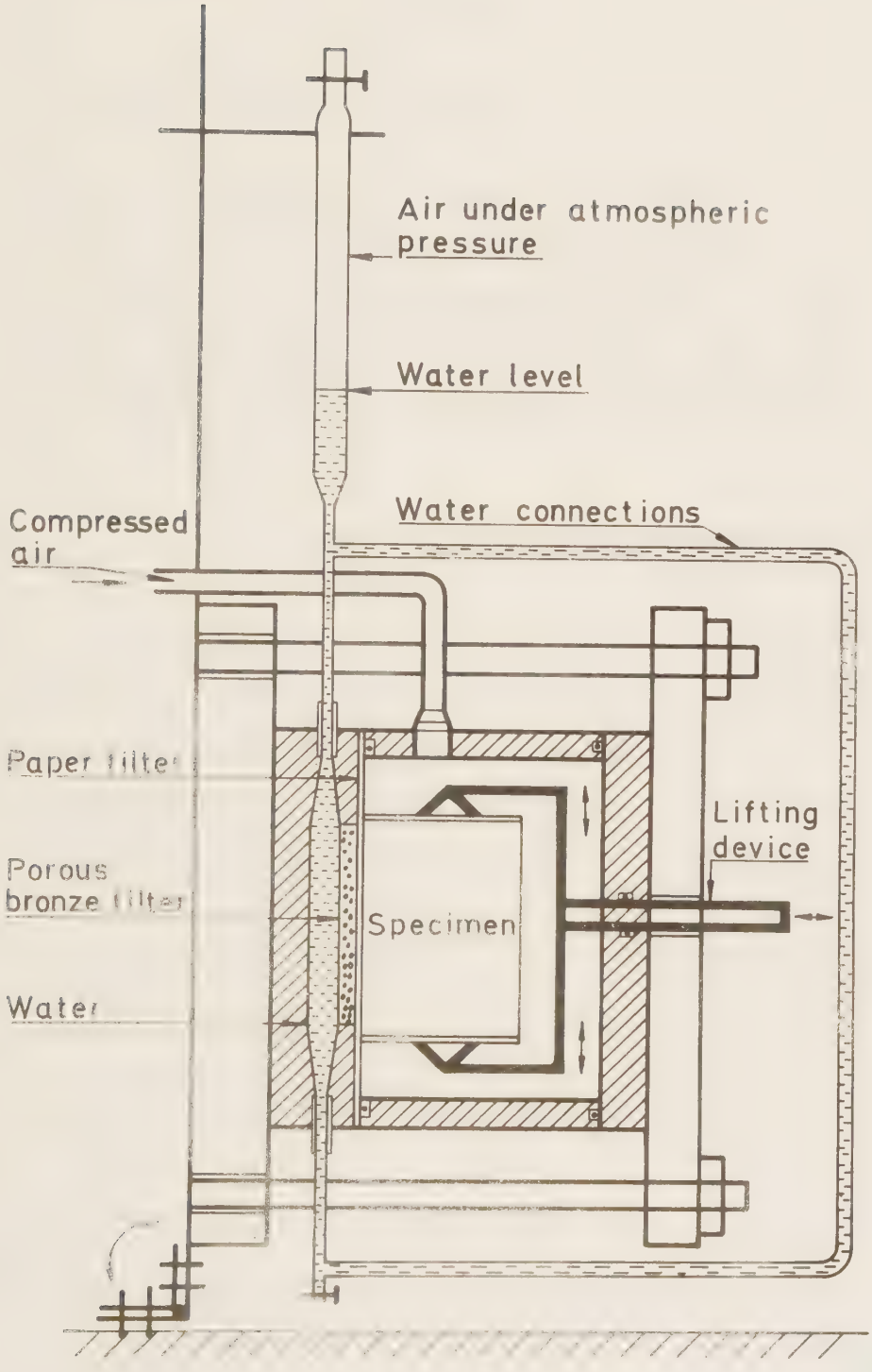


Fig. 7. The pressure plate apparatus built at the Lund Institute of Technology.

This concept was originally defined as follows:

$$pF = \log_{10} h$$

and

h = water underpressure expressed in centimeters of head of water.

Both sorption isotherms and retention curves represent the same physical problem, namely they describe energy of water filling a certain part of the pore system. As the thermodynamic potential is the same for water, both in liquid and in vapour phase, both forms of energy description may be easily recalculated, one into the other. An example of such a recalculation is shown in table 1-1.

TABLE 1-1. Correlation between capillary suction, pF-value and relative humidity.

pF -	capillary suction N/m^2	relative humidity %
$-\infty$	0	100,0
0	$0,98\times10^2$	>99,99
1	$0,98\times10^3$	>99,99
2	$0,98\times10^4$	99,99
3	$0,98\times10^5$	99,92
4	$0,98\times10^6$	99,27
5	$0,98\times10^7$	93,00
6	$0,98\times10^8$	48,43
7	$0,98\times10^9$	<0,1

Suction and relative humidity may be easily recalculated, but normally only the sorption isotherm is tested for building materials.

Table 1-2 shows a usual range of test results against the total open pore volume.

TABLE 1-2. Moisture equilibria at 98 % R.H. compared with the open pore volume.

Material description	moisture content at ϕ = 98 % R.H.	max. moisture content
Aerated concrete with density 500 kg/m^3	50-80	670-740
clay bricks $\rho \approx$ 1800 kg/m^3	7-10	250-330

As shown in table 1-2 the sorption isotherms relate only to a small part of the total pore-volume accessible to moisture. A more complex testing (containing a complete retention curve) would need to be carried out for a number of technical applications.

The osmotic forces should also be considered while discussing moisture equilibria.

An example of the influence of salts on the moisture equilibria within the hygroscopic moisture content is shown in Fig. 8.

Discussing moisture equilibria as tested by means of liquid water transport, the air entrapment should also be taken into consideration.

The following mechanisms concerning the amount of entrapped air should be recognized:

1) Air in contact with water tends to reach an equilibrium with the air in solution in water.

2) Air in solution diffuses through the water if an air concentration gradient exists.

3) If other conditions permit, air bubbles are transported through the water field.

4) Evaporation and condensation can either open or seal the connections between air bubbles and ambient air.

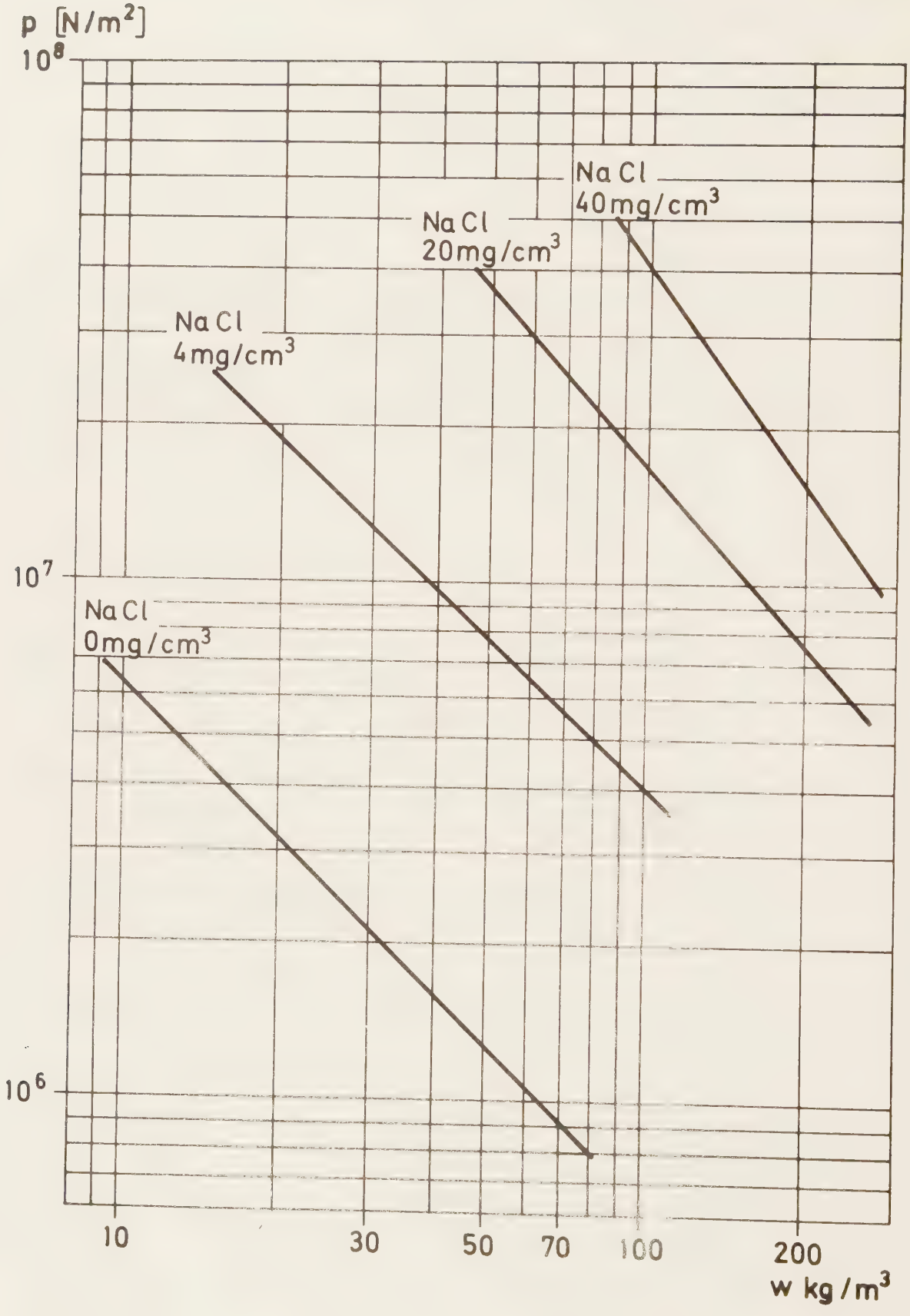


Fig. 8. Moisture retention curve of clay-bricks with different concentration of NaCl. After Vos & Tammes (1969).

Air entrapment appears to be of different significance for small and large pores. Bloomsburg & Corey (1964) analysed the time necessary to dissolve an air bubble as a function of its radius and stated that

for $r = 10^{-5}$ m, t = 7 sec;
for $r = 10^{-4}$ m, t = 98 min;
for $r = 10^{-3}$ m, t = 67 days.

Further, it may be assumed that the air phase influences the volume of water in equilibrium at any given time and the water distribution inside the specimen. This aspect is illustrated in Fig. 9 where water intake to the aerated concrete specimen is illustrated.

Moisture content increases quickly to a level of about 300 kg/m^3, but slowly above this level. The open porosity for this material is equal to about 0,70 m^3/m^3, i.e. maximum moisture content is 700 kg/m^3.

It is evident that the total open pore volume is not immediately available for the water transport. At a certain moisture content a free path of air outflow becomes interrupted and the air becomes isolated in the water phase. The volume of pores occupied by air will be available for the water only when the air leaves it.

Finally, Thompson's law may be recalled and expressed in the following way

$$\Delta f = R_v \, T \ln \frac{c_{cs}}{c_s} , \qquad (2)$$

where

Δf = increment of the free energy due to the curvature of the meniscus, J/kg
R_v = gas constant for water vapour, J/kg K
T = temperature, K
c_{cs} = saturated vapour concentration above the capillary meniscus, kg/m^3
c_s = saturated vapour concentration above the free water surface, kg/m^3

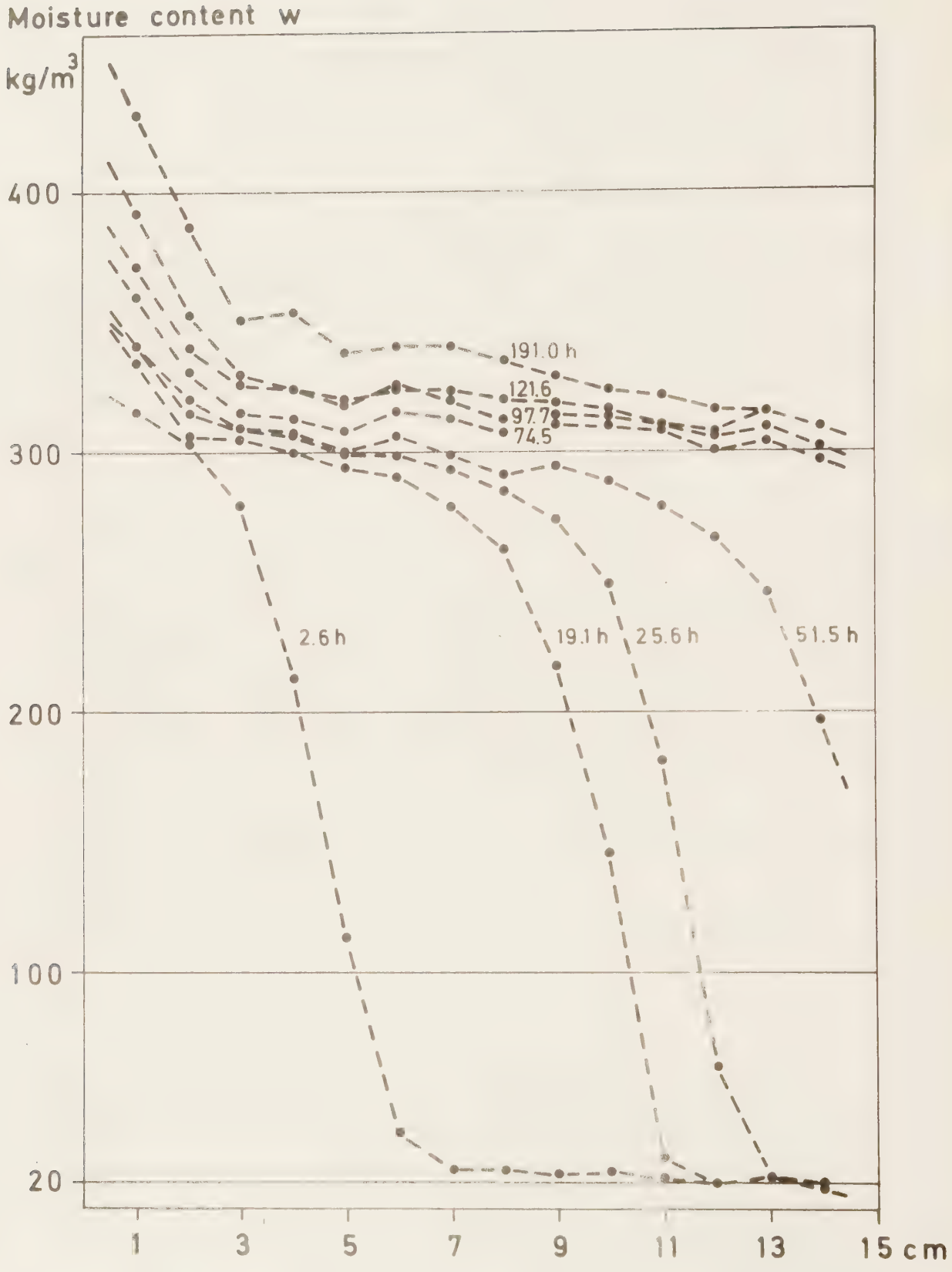


Fig. 9. Moisture distributions in aerated concrete during water intake to the insulated specimen. The tests performed by A.F. Nielsen and the author at the Thermal Insulation Laboratory, Danish Institute of Technology.

Thompson's law shows that the maximum vapour concentration in the smallest pores is decreased and condensation occurs even if the relative humidity of surrounding air is much less than 100 %.

Condensation will occur inside the pores at the following values of relative humidity in the ambient air:

radius $r = 1 \times 10^{-6}$ m at $\phi = 99{,}9$ %
radius $r = 1 \times 10^{-8}$ m at $\phi = 90$ %
radius $r = 1{,}2 \times 10^{-9}$ m at $\phi = 40$ %

This condensation may be negligible up to a certain level of relative air humidity but above that level it may play an influential role on the WVT (water vapour transmission). According to Harmathy (1967), "For $\phi > 0{,}4$ capillary condensation is the principal mechanism of adsorption".

2.2 Isothermal moisture transport.

2.2.1 Single phase or multiphase transport.

A vapour diffusion is related to a vapour concentration gradient. The concentration of vapour inside the porous materials is, however, determined by the moisture content. The question arises whether it is really necessary to know both these gradients or whether it is enough to analyse only one of them. (We do not discuss freezing in this report.)

Tests carried out at the Lund Institute of Technology compare a vapour diffusion with a total moisture transport. In the later, both phases contribute to the mass flow.

Two specimens were connected face to face: (i) the standard one, with the equilized and known moisture content distribution, and (ii) the tested one, originally dry. Both specimens were insulated at all other sides so that no moisture exchange could take place to the outer air. Moisture exchange between the specimens could take place in two ways, either by a direct contact or via an approximately 1 mm thick air space, which permitted only a vapour phase transport.

Fig. 10 and 11 show the contact tests between the standard gypsum and wood fibre board. A total transport produces quicker increase in the moisture content, but the difference between this transport and diffusion is relatively small. Both kinds of the moisture transport are relatively slow. 2000 hours seems evidently too short time for reaching equilibrium.

Fig. 12 shows the contact tests between the standard gypsum and aerated concrete. In this instance a difference between total transport and vapour diffusion is large. Equilibrium state was reached after 300-400 hours as result of total moisture transport, while during 2000 hours of vapour diffusion equilibrium was not achieved.

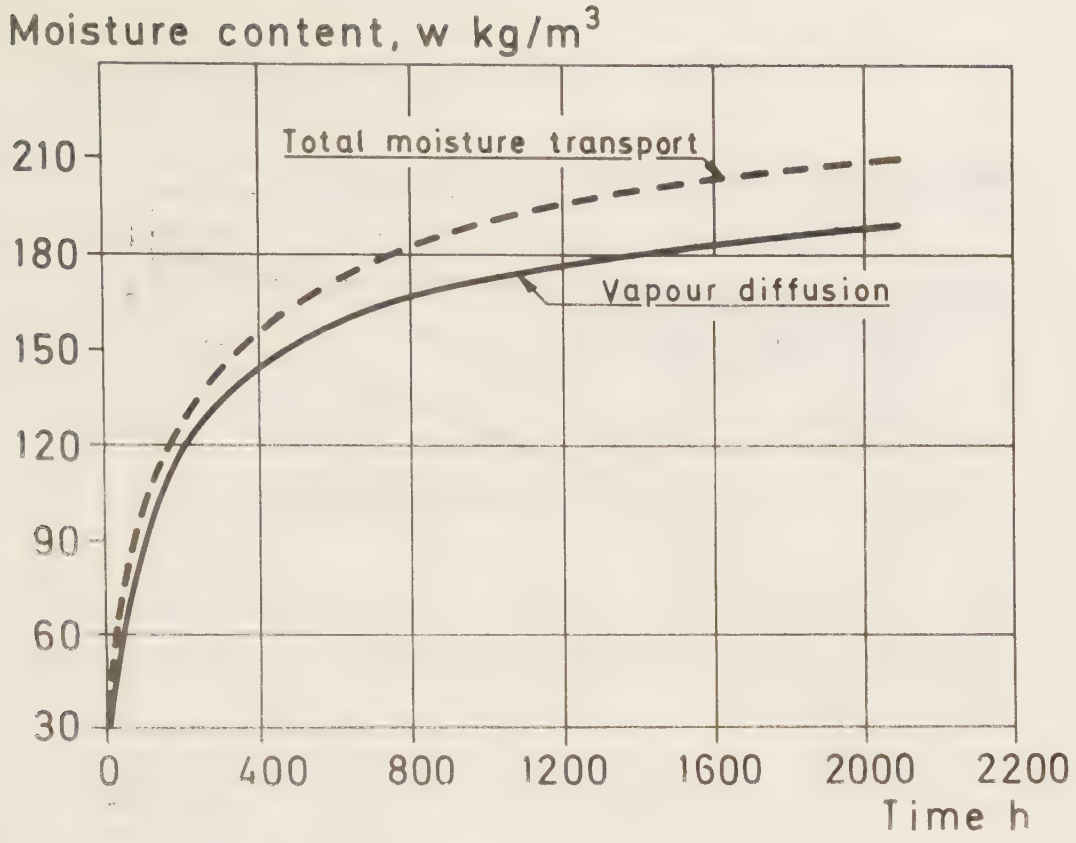


Fig. 10. Contact tests between the standard gypsum (density about 1250 kg/m^3, open porosity 0,44 m^3/m^3) and wood fibre board. Starting moisture content of the gypsum 420 kg/m^3.

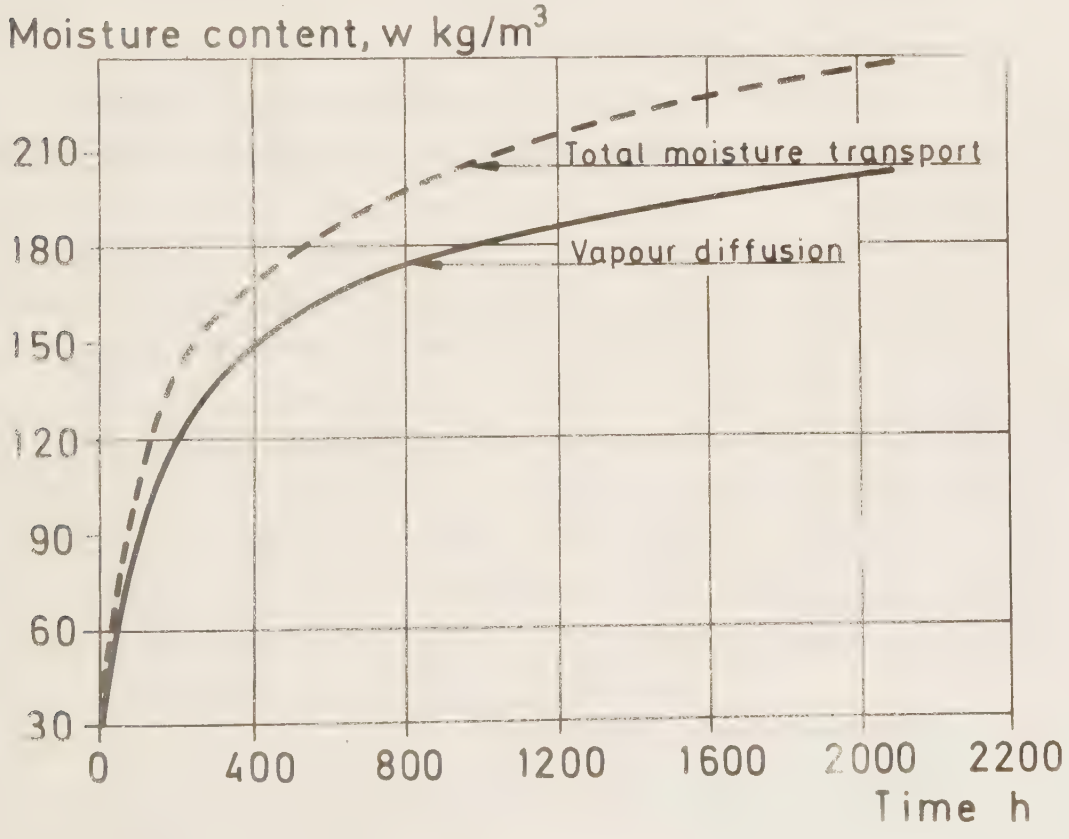


Fig. 11. Contact tests betwwen the standard gypsum (density about 1250 kg/m^3, open porosity 0,44 m^3/m^3) and wood fibre board. Starting moisture content of the gypsum 320 kg/m^3.

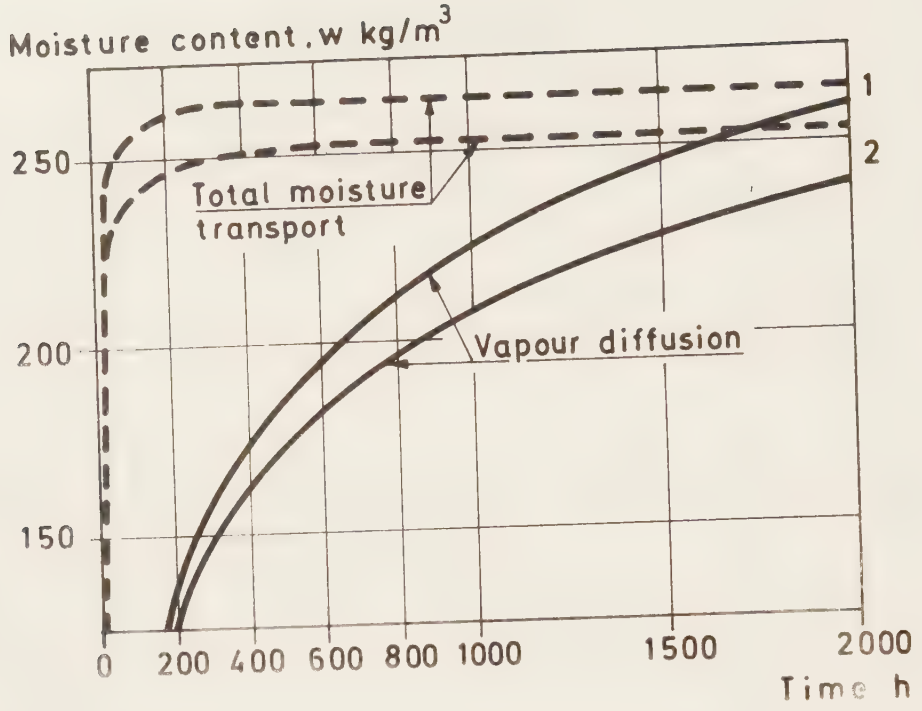


Fig. 12. Contact tests with the standard gypsum (density about 1250 kg/m^3, open porosity 0,44 m^3/m^3).
Moisture content 1. w = 420 kg/m^3, 2. w = 320 kg/m^3.
Tested aerated concrete with density about 500 kg/m^3.

It may be seen in Fig. 12 that the state of equilibrium obtained by means of total transport will be reached also by diffusion, however, after a much longer time.

Water vapour and water liquid potentials are the same. Therefore, after a sufficiently long time the same moisture content is reached. The fact that the thermodynamic potential is the same is well known, but its practical consequences are seldom realized, perhaps because of the differences in time necessary to reach the equilibrium moisture content. As the velocity of the transport is usually calculated for a certain type of flow, different kinds of moisture flow will be reviewed below under the following headings:

water vapour diffusion through an air layer,
water vapour transport (WVT) trough porous materials,
water vapour convection,
water transported in liquid phase

2.2.2 Water vapour diffusion through an air layer.

Water vapour diffusion may take place through a layer of a still air when:

a) On both sides of this layer the transport continues in the vapour phase (no phase exchange); called equimolar diffusion because the same molar quantities of two (or more) gases are involved.

b) A phase exchange takes place; called non-equimolar diffusion.

In (a), air and vapour are expected to mix until their concentrations (partial pressures) are equalized. This process is described by Fick's law:

$$q_{m,v} = - D_{va} \frac{dc}{dx} \qquad (3)$$

where:

$q_{m,v}$ = density of the vapour flow rate, kg/m^2s
D_{va} = diffusivity of water vapour in air, m^2/s
c = vapour concentration in air, kg/m^3
x = distance along the diffusion streamline, m.

In (b) diffusion takes place when water evaporates from a water surface or capillary menisca. This process is described by Stefan's law, which may be written in the following way, Krischer (1963):

$$q_{m,v} = - D_{va} \frac{p_{tot}}{p_{tot} - p_v} \frac{dc}{dx} \qquad (4)$$

where:

p_{tot} = total pressure of the air-vapour mixture, N/m^2
p_v = partial pressure of water vapour, N/m^2

As p_v is usually much less than p_{tot} the difference between Eq. (3) and Eq. (4) is currently neglected.

2.2.3 Water vapour transport (WVT) through porous materials.

a) Stationary flow.

This is basically the same process as the vapour diffusion through still air. Flow resistance depends on the material structure and Fick's law may be written in one of the following forms

$$q_{m,v} = - \delta \frac{dc}{dx} \qquad (5)$$

or

$$q_{m,v} = - \frac{D_{va}}{\mu} \frac{dc}{dx} \qquad (6)$$

where

δ = vapour conductivity coefficient describing diffusion of vapour through the porous system, m^2/s

μ = coefficient describing the effect of the pore structure on the diffusion rate (ratio between density of the flow rate through air and through the material, it is larger than 1).

b) Non-stationary flow.

A retardation of the movement of vapour molecules through the pore system was the only contribution of the material to the steady state flow. The diffusion coefficient alone could describe this flow.

A further characteristic requires to be known for non-stationary flow i.e. how much water may be stored inside the material when a certain increase of vapour concentration occurs, or how much water will leave the material if a certain decrease of vapour concentration takes place.

Moisture flow through porous material may be related to a moisture gradient as follows:

$$q_m = - D \frac{dw}{dx} \qquad (7)$$

where:

D = moisture diffusivity coefficient, m^2/s.

Eq. (7) is independent on the transported phase and describes the total moisture transport. Assuming, however, that such a low moisture content is discussed where the liquid phase transport may be omitted, Eq. (7) may also describe the vapour phase transport. Omitting hystereses, the following equation may be written as a development of Eq. (7):

$$q_{m,v} = - D_v \frac{dw}{d\phi} \frac{1}{c_s} \frac{dc}{dx} \qquad (7a)$$

If introducing the vapour differential capacity:

$$\xi = \frac{dw}{d\phi} \qquad (8)$$

and comparing Eq. (5) with Eq. (7a), the vapour diffusivity coefficient is obtained as follows:

$$D_v = \frac{\delta c_s}{\xi} \qquad (9)$$

The differential vapour capacity for aerated concrete is illustrated in Fig. 13.

The vapour conductivity coefficient δ is nearly constant for the hygroscopic moisture content range (Tveit, 1966). Saturated vapour concentration is also constant, if the temperature is constant. Nevertheless, the vapour-phase diffusivity coefficient is strongly variable due to alterations in the differential vapour capacity as shown in Fig. 13. Fig. 15 shows the diffusivity coefficient for vapour phase transport according to Vos & Cruys (1967) who recalculated tests of Mahler (1958).

Calculations with a constant and variable vapour-phase diffusivity coefficient were carried out by Chlusov (1958). His investigations were concerned with a roof of the aerated concrete where the capillary condensation had occurred during period of 49 days. The measured and calculated moisture content distributions are shown in Fig. 14.

The calculation based upon differential vapour capacity gave a agreement with test results. This concept was also used by Lund-Hansen (1967).

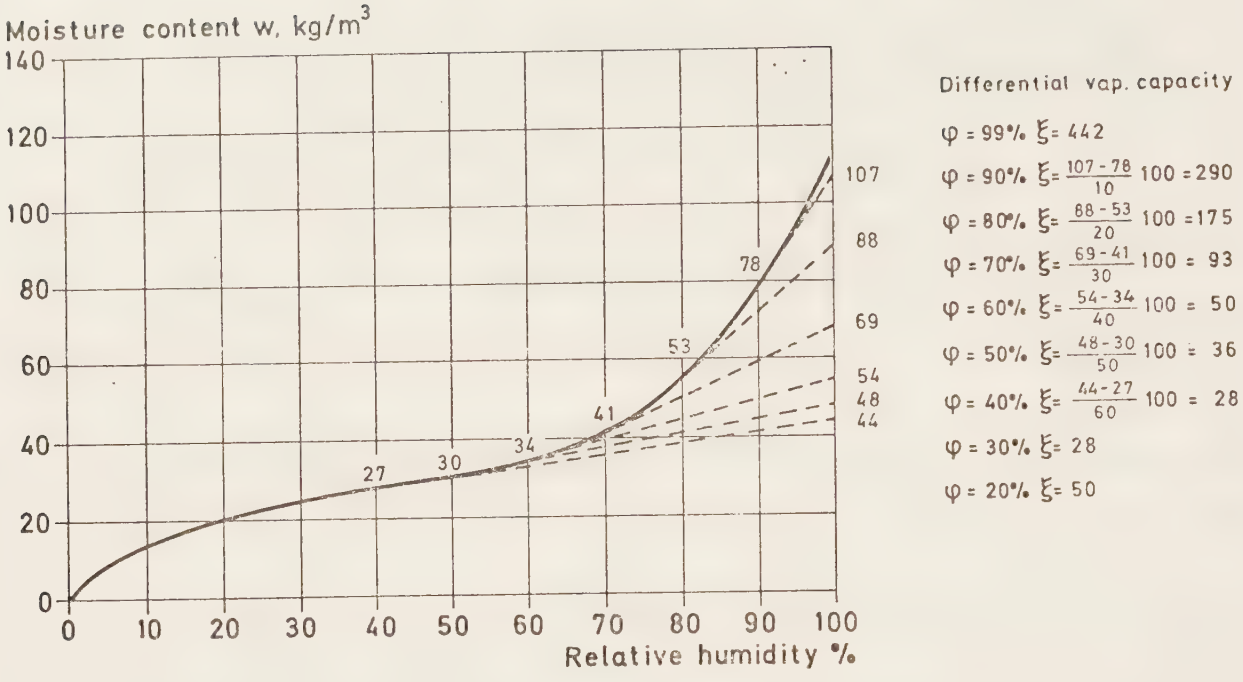


Fig. 13. Calculation of the differential vapour capacity for aerated concrete with density 750 kg/m^3. After Chlusov (1958).

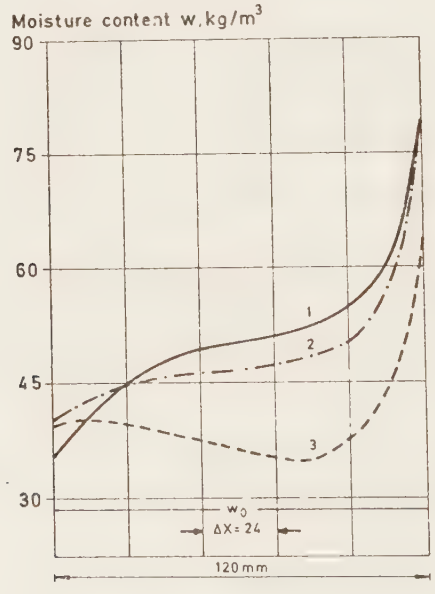


Fig. 14. Moisture distribution in the roof structure of aerated concrete.
1. Measured. 2. Calculated with ξ-value from Fig. 13.
3. Calculated with constant ξ-value. After Chlusov (1958).

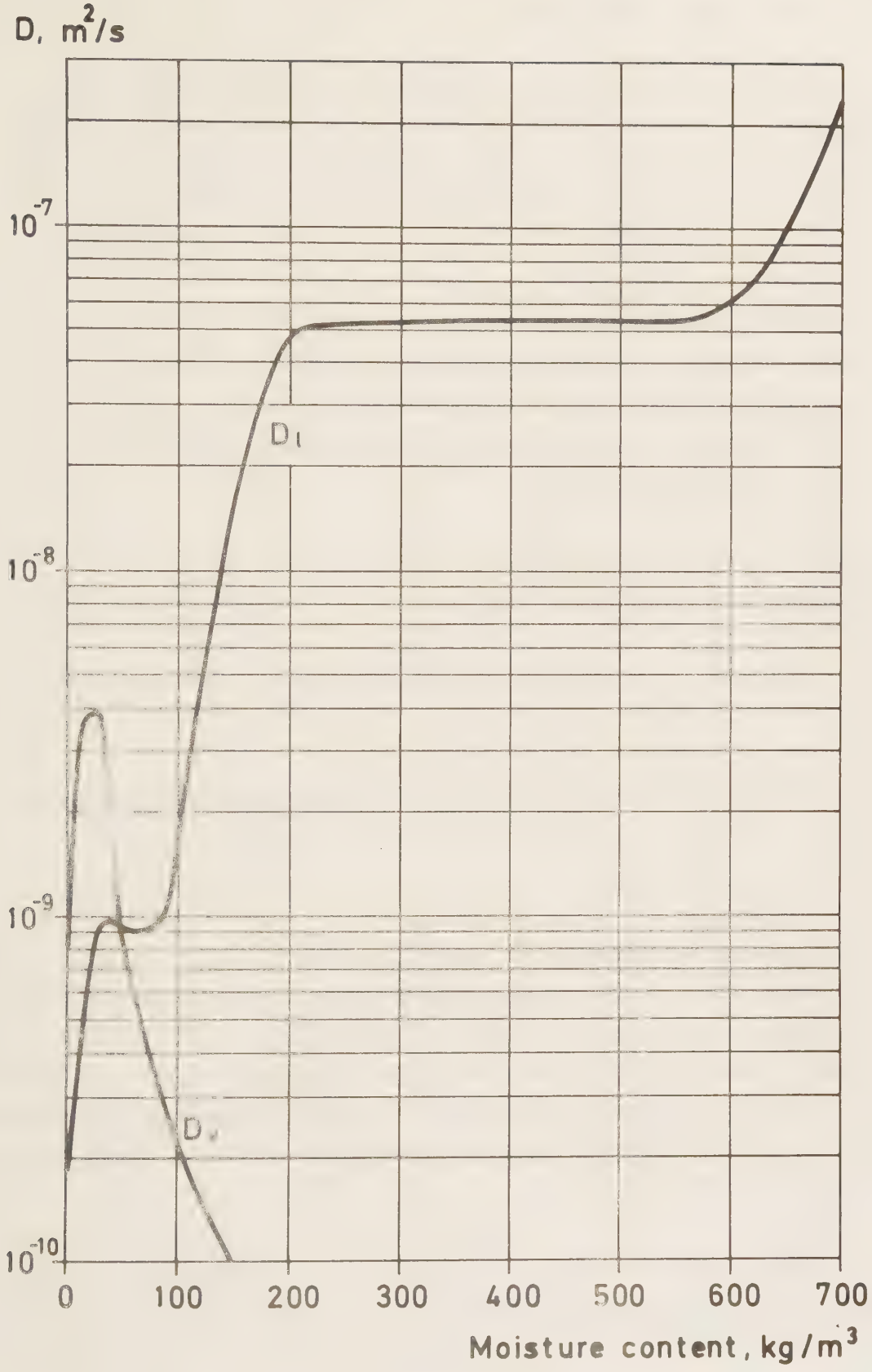


Fig. 15. Liquid phase (D_l) and vapour phase (D_v) diffusivity for aerated concrete with density 650 kg/m^3. After Vos & Cruys (1967), tests of Mahler (1958).

2.2.4 Water vapour convection.

This term is sometimes used to describe the amount of water that is transported by air stream. Incompressibility of the air and a simple viscosous flow pattern are usually assumed in this calculation. Thus, the water vapour convection may be expressed as follows:

$$q_{m,v} = - \kappa_a \frac{c}{\rho_a} \frac{dp_a}{dx} \qquad (10)$$

where:

$q_{m,v}$ = density of vapour flow rate, kg/m^2s
c = vapour concentration in the air stream, kg/m^3
ρ_a = air density, kg/m^3
κ_a = air conductivity, s
p_a = air pressure, N/m^2
x = distance along streamline, m.

Moisture convection appears important only when the structure contains air cavities and ventilated air spaces.

Moisture convection is not included in the model discussed in Chapter 5.

2.2.5 Liquid water transport.

Thickness of the adsorbed water layer increases directly with increasing relative humidity. At a certain relative humidity level this layer is thick enough to start a liquid flow in some of the smallest pores. With a further increment of the R.H.-level this flow starts also in increasingly larger capillaries, becoming at a certain stage a thorough liquid flow. It is often called a capillary water flow or an unsaturated water flow.

It is assumed that the unsaturated water flow is described by a generalization of Darcy's equation (which originally was introduced only for the saturated hydraulic flows), then this equation may be written as follows:

$$q_l = - k (w, T, a) \frac{dp}{dx} \qquad (11)$$

where

k = moisture conductivity coefficient, s
T = temperature, K
a = air content, kg/m^3
w = moisture content, kg/m^3
p = suction, N/m^2

The water conductivity (permeability) coefficient, which was constant in Darcy's law is expected to be a function of moisture content and perhaps also a function of some other factors, such as air content in the water phase and temperature. The water overpressure (hydraulic head) is replaced by water suction.

Bearing in mind Eq. (7) and assuming the moisture suction being a single-valued function of moisture content the differential moisture capacity may be defined as follows:

$$e = \frac{dw}{dp} \qquad (12)$$

and a relation between the moisture diffusivity and conductivity coefficients acquires a following, generally valid form

$$D = \frac{k}{e} \qquad (13)$$

The above dependence would be evident if for each value of the moisture content only one value of the suction and the conductivity coefficient were present. As known, however, a range of values of the suction may be obtained for the same value of the moisture content. The material properties in Eq. (7) and Eq. (11) are determined in such a different tests that other factors involved may cause discrepancies between these moisture characteristics.

Vachaud (1968, p. 141) introduced the "coefficient of static diffusivity" as follows:

$$D_* = k \frac{\partial p}{\partial w}$$

in addition to the coefficient D "dynamic conductivity" defined by the equation:

$$q_m = - D \frac{\partial w}{\partial x} \qquad (7)$$

He stated that "For a given water content D and D_* are not identical except if p(w) is unique for a dynamic transistory flow and for static equilibrium".

Different techniques for determination of the transport coefficients do not lead to different results if the hysteretic background is the same. This was proved by Chow & Vries (1972) in the case of clear drying and clear wetting.

Finally, we conclude that as the liquid phase transport appears to be fully analogous to the previously discussed vapour transport, and as the potential is the same for both phases, it will be possible to treat both phases together.

3 NON-ISOTHERMAL CONDITIONS.

3.1 Moisture equilibria.

Moisture equilibria may be influenced both by changes in temperature level and gradient.

A change in the average temperature level leads to relatively small correction in the equilibrium moisture content, as it slightly changes the moisture potential.

If moisture content is held constant, the pore-water meniscus would not be expected to change its configuration significantly, and the following equation may be written (Wilkinson and Klute, 1962):

$$\left(\frac{\partial p}{\partial T}\right)_w = p \frac{1}{\sigma} \frac{\partial \sigma}{\partial T} \qquad (14)$$

Even though the air entrapment makes the above calculation less accurate (Chahal, 1964), it appears to be sufficiently good for the range of temperature variations occurring in building technology.

A difficulty arises when analyzing the influence of a temperature gradient.

To assess the influence of the temperature gradient influence on the moisture equilibria, tests carried out by Hanson (1957) are described below.

A specimen with one open side (the warmer) was exposed to a constant temperature gradient (see Fig. 16).

A thermally driven flow forced the moisture (being in equilibrium at the open surface) to start redistributing inside the specimen and to continue as long as the total energy balance was not equalized. The thermally driven flow transferred moisture towards the cold side of the specimen, until such a large moisture content gradient was created, that an opposite flow of an equal density rate become induced. Thus the total weight of the specimen became steady and the equilibrium state was reached. By cutting the specimen into pieces Hanson determined the moisture content distribution, as shown in Fig. 17.

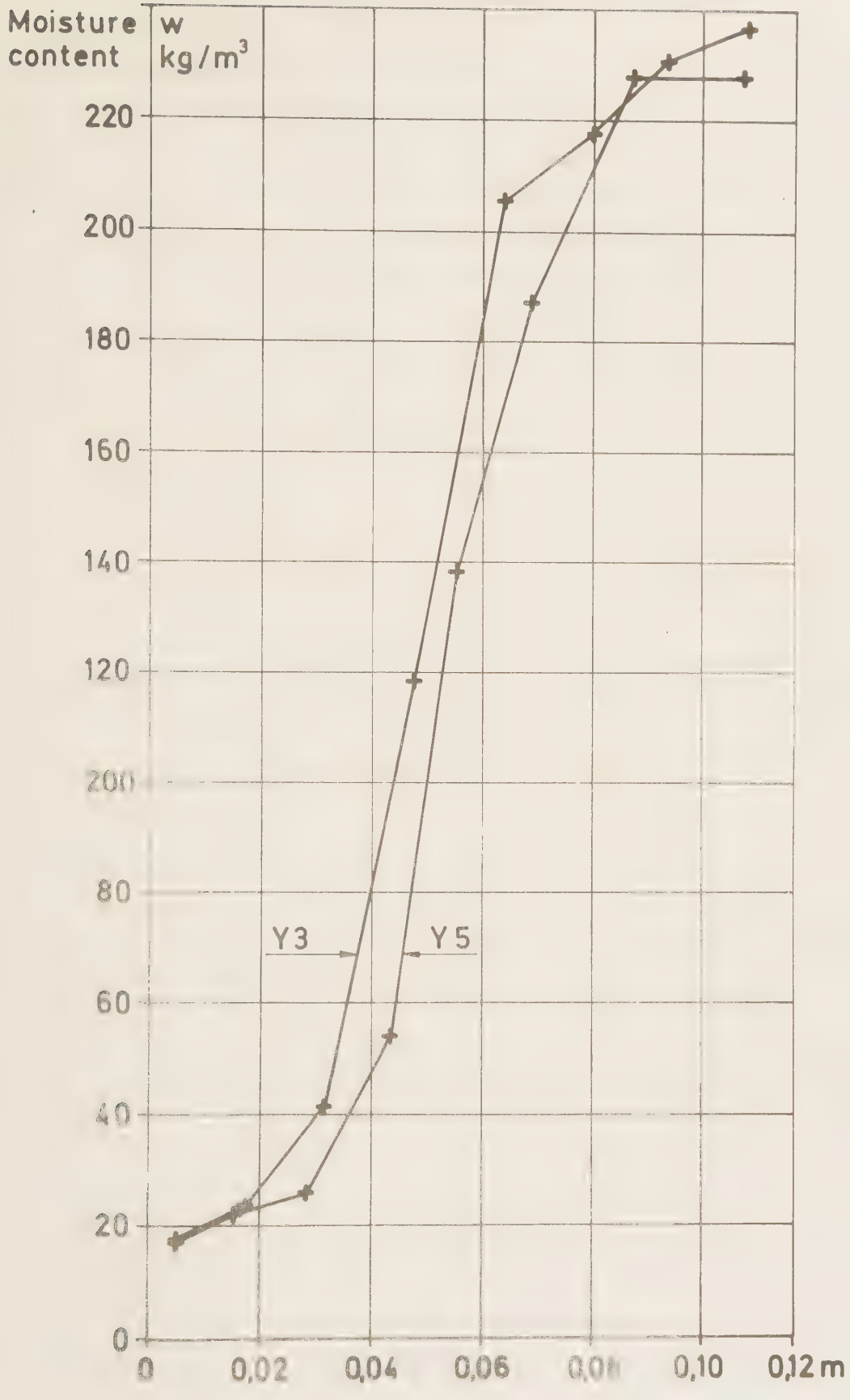


Fig. 17. Moisture content distribution in aerated concrete exposed to the temperature gradient as shown in Fig. 16. The cold side was sealed, the warm open to the air with relative humidity $\phi = 0.425$. Results of Hanson (1957).

The sum of a capillary suction and a suction equivalent of the temperature gradient had the same value over the whole specimen. If the isothermal capillary suction is known (a function of moisture content), the suction equivalent of the temperature gradient may be calculated.

Moisture equilibria may also be calculated if the moisture diffucivity related to temperature gradient is known and the termally driven moisture flow may be determined. This aspect is discussed in the following chapter.

3.2 Thermally driven moisture flow.

There are several ways to approach the problem of non-isothermal moisture transport. One may either introduce suction equivalent of the temperature gradient as a new part of the total suction, or introduce a new member to the flow equation, containing a temperature gradient multiplied by a coefficient of moisture diffusivity related to temperature gradient. Both procedures are exactly the same. For both the relationship between the flows caused by a temperature gradient and a moisture content gradient must be known. In a dynamic equilibrium, when both temperature and moisture content gradients cause opposite flows and the resulting flow is equal to zero, the following equation may be written:

$$-(D \frac{\partial w}{\partial x} + D_T \frac{\partial T}{\partial x}) = 0 \qquad (15)$$

where:

D = isothermal moisture diffusivity

D_T = thermal moisture diffusivity, i.e. moisture diffusivity related to temperature gradient

Eq. (15) may also be written as follows

$$- k \frac{\partial p}{\partial x} - D_T \frac{\partial T}{\partial x} = 0 \qquad (16)$$

The above equations correlate four variables, two transport coefficients and two potential gradients.

When both gradients and isothermal transport coefficient are known the transport coefficient for the thermally driven flow may be determined as follows:

$$- D(\frac{\partial w}{\partial x} + \beta \frac{\partial T}{\partial x}) = 0 \qquad \text{i.e.} \quad D_T = \beta D \qquad (17)$$

$$- k(\frac{\partial p}{\partial x} + \gamma \frac{\partial T}{\partial x}) = 0 \qquad \text{i.e.} \quad D_T = \gamma k \qquad (18)$$

at dynamic equilibrium become the coefficients β and γ as follows:

$$- \beta(w, T) = \frac{dw}{dT} \qquad (17a)$$

$$-\gamma(w, T) = \frac{dp}{dT} \qquad (18a)$$

The character of β-curve is similar to γ-curve. Some tests of Dubintsky reported by Lykow (1964); Cary & Taylor (1962), Gee (1966) and others reported in Chapter 5 of Soil Water (1972) give informations about these curves.

The curve increases at first, passes through a maximum and then decreases to zero at full saturation. It is only slightly dependent upon the temperature level. An example of a β-curve is shown in Fig. 18.

No simplification was introduced in the above approach, nevertheless there are some experimental conditions which indirectly make the above approach inexact.

The relationship between thermally driven and isothermal moisture flows must be tested in a dynamic equilibrium and only two potentials may be involved. Neither pressure of the entrapped air, nor the hysteretic background may influence the dependence of two transport coeffic ents and suction upon moisture content of the material.

Unless the above conditions are fulfilled, one may find that calculations based on the experimentally determined β-curve deviats more or less from the measured values (see Chapter 5 of Soil Water, 1972).

In particular, determination of β-coefficient is doubtful in the area where obstruction to air flow occurs, i.e. above the bubbling point.

This approach is limited to nearly the same range of moisture content as when the vapour phase transport is considered. It is, however, advantageous to attribute the whole influence of the temperature gradient to the vapour phase movement. In such a case the dynamic equilibrium tests are not necessary.

The thermally driven flow may be calculated on the basis of material properties determined during the isothermal vapour transport.

If vapour transport is assumed as the only important part of moisture

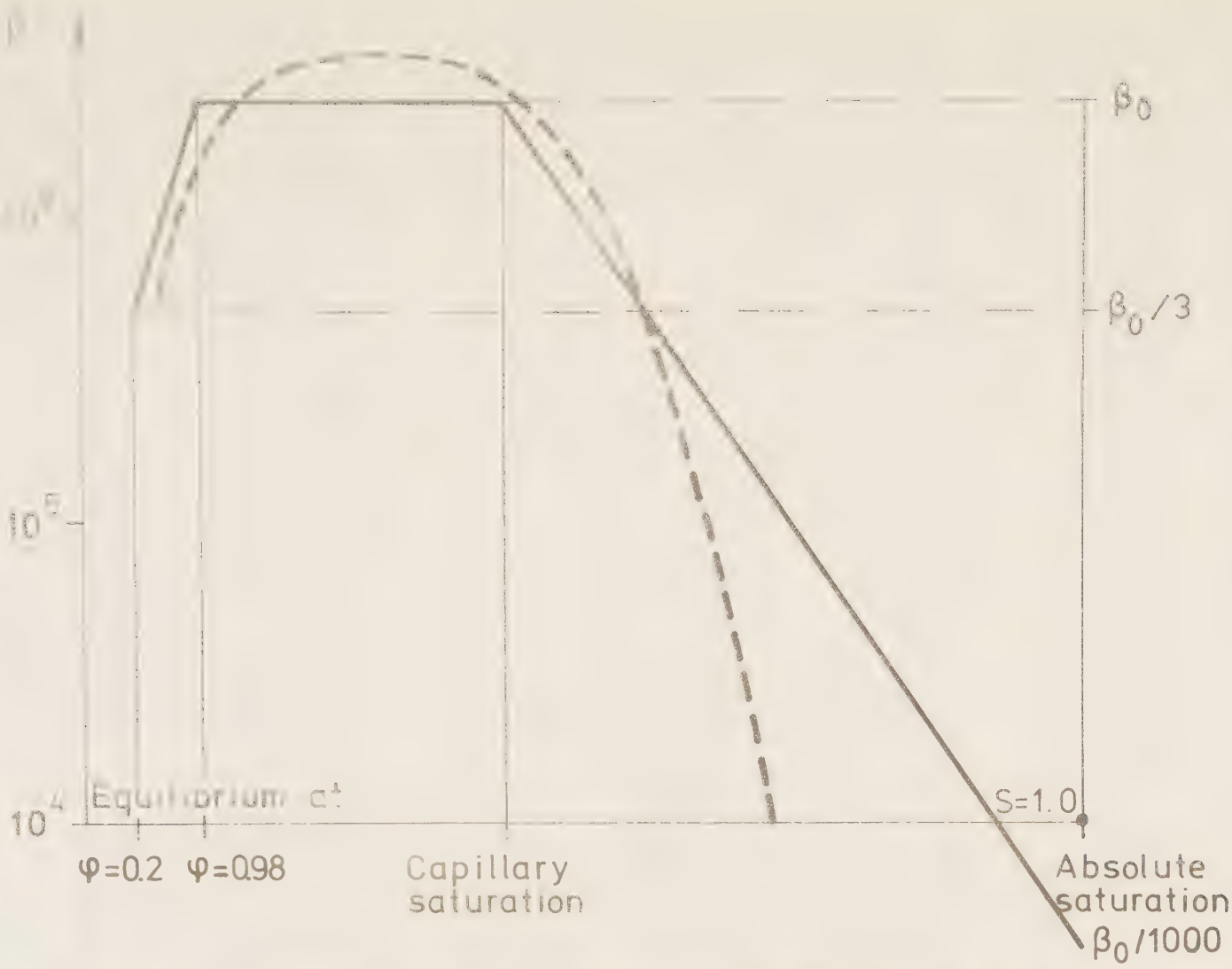


Fig. 18. Ratio between suction and temperature gradients calculated for aerated concrete with density about 700 kg/m^3, on the base of dynamic equilibrium tests of Hanson (1958) and moisture retention curves of van der Kooi (1971). Loop of the curve is shown against the approximation used in the calculations.

transport the following equation may be written

$$\delta_n \frac{\partial c}{\partial x} = k \frac{\partial p}{\partial x} \qquad (19)$$

where:

$$p = \rho R_v T \ln \frac{c}{c_s}$$

and δ_n-coefficient is a function of temperature and moisture content (compare k-coefficient in Eq. (11)). Out of Eq. (19) follows

$$k = \frac{\delta_n c}{\rho R_v T} \qquad (20)$$

An equation concerning the dynamic equilibrium may be written as follows:

$$- k \frac{\partial p}{\partial x} = D_T \frac{\partial T}{\partial x} \qquad (16)$$

and substituting Eq. (20), a moisture diffusivity coefficient related to temperature gradients obtains the following formula:

$$D_T = - \frac{\delta_n}{\rho R_v T} \frac{\partial p}{\partial T} \qquad (21)$$

or

$$D_T = - \frac{\delta_n}{T} \left(\ln \phi - T \frac{1}{c_s} \frac{\partial c_s}{\partial T} \right) \qquad (21a)$$

Presence of a temperature gradient causes condensation and evaporation to take place in a large number of pores, even if the moisture content of the material does not exceed the hygroscopic moisture.

If relative humidity of air is equal to about 99 %, the logarithm is less than 0,01 and the first term in Eq. (21a) may be neglected. The coefficient of moisture diffusivity related to temperature gradient may be approximately expressed as follows:

$$D_T = \delta_n \frac{dc_s}{dT} \frac{c}{c_s} \qquad (22)$$

Introducing $c_s = c_s(T)$ one obtains approximate formula for the thermal moisture diffusivity, for instance for a temperature range between 263 and 298:

$$D_T = \delta_n \frac{0,1056}{T} \left(1 + 0,02\ (T-273)\right)^3 \qquad (23)$$

Eq. (23) may be compared with the following equation quoted in Soil Water (1972) p. 106

$$D_T = f_o\ \delta \frac{p_v}{R_v\ T} \frac{d \ln p_v}{dT} \qquad (24)$$

where:

f_o = a dimensionless factor depending upon the tortuosity of the pores, the air filled pore-volume and the increase in microscopic thermal gradients across the air space. The f_o-values for different moisture contents of soils vary between 0,9 and 5.

The same effect as expressed by f_o in Eq. (24) is included in Eq. (23) in the coefficient δ_n, which describes the water vapour transmission (WVT), not the equimolar vapour diffusion determined by the dry-cup method. The actual WVT where the liquid phase transport contributes may produce a vapour conductivity being a function of moisture content of the same magnitude as shown in Soil Water (1972), see: Joy & Wilson (1965).

It is necessary to determine at least two values of δ : one at relatively low, the other at possibly high level of the relative humidity. It may be done by testing a steady state vapour diffusion through a specimen exposed to different vapour concentrations, e.g. 75 and 95 % R.H. on either side. Alternatively wet-cup permeability (50 and 99,9 % R.H.) may be adequate. Informations about only the dry-cup permeability may be insufficient to describe the δ_n-coefficient as function of moisture content in the hygroscopic region.

If nothing is known about dependence of the vapour permeability on moisture content and only the dry-cup permeability is known, the following assumptions will be used for calculational purposes.

The thermal moisture diffusivity coefficient is divided into three parts with different dependence on the moisture content. The real changes of D_T are assumed to be as follows (cf. Fig. 18):

(i) The thermal moisture diffusivity increases between the lower limit of calculations and equilibrium moisture content at ϕ = 98 % R.H.. When not measured, this increment is assumed to be 300 % of the lowest value.

(ii) $D_T = D_T(\delta,T)$ according to Eq. (23) i.e. constant level for moisture contents higher than hygroscopic but not higher than capillary saturation.

(iii) From this level at the capillary saturation, the thermal moisture diffusivity decreases to zero value at the absolute saturation.

4 CALCULATIONAL MODELS.

4.1 Single phase flow.

A moisture exchange between material and environment may be approximatively described by taking into consideration either vapour or liquid phase transport.

4.1.1 Vapour phase transport.

A vapour phase transport is described by the following equation:

$$g_m = -\left(\delta \frac{\partial c}{\partial x} + D_T \frac{\partial T}{\partial x}\right) \qquad (25)$$

In the above equation vapour concentration (c) represents the actual concentration inside the pores, not the mean value of the ambient air on either side of the specimen.

The calculations can not be simplified by the assumption that the actual vapour concentration inside the porous material is simply distributed in relation to vapour resistance:

$$Z_v = \frac{d}{\delta} \qquad (26)$$

where:

d = thickness of the layer
δ = vapour conductivity coefficient.

The calculations may omit the second term in Eq. (25) describing the thermally driven flow and introduce relative humidity instead of the vapour concentration in the first term of Eq. (25). Relative humidity is, however, determined by the moisture content of the material, and vapour differential capacity is introduced into the calculations.

Assuming the steady state, the vapour differential capacity is disregarded and vapour diffusivity is assumed to be constant, as discussed in Chapter 2.2.3.

Another drawback of a vapour diffusion model is that it does not take account of the liquid flow which occurs, for instance, if a condensation process takes place.

A few methods of calculations, both regarding and disregarding the vapour differential capacity were compared and analysed by Sandberg (1973).

4.1.2 Liquid phase transport.

The liquid phase flow is usually described as follows

$$g_{m,l} = - D \frac{dw}{dx} \qquad (7)$$

were the thermally driven flow is omitted (see Eq. (15)).

This model has a relatively limited range of applications because it can not describe a flow through a multilayered structure. The moisture potential (suction) has to be known for a description of the conditions at the surface of contact between different materials.

4.2 Models based upon mixing of simple phases.

The following equation may be written but is rarely applicable in practice

$$q_m = - \left(\delta \frac{dc}{dx} + k_l \frac{dp}{dx} + D_T \frac{dT}{dx} \right) \qquad (27)$$

where:

δ = vapour conductivity coefficient
k_l = liquid conductivity coefficient
D_T = moisture diffusivity coefficient due to a temperature gradient

The coefficients describing different phases are interconnected. Vapour and liquid phase potentials are also interconnected, because the vapour concentration in the pores depends on the moisture content of the material.

The above model may be useful under certain conditions:

(a) if the vapour conductivity is assumed to be constant, and

(b) the rest of the moisture is transported in a liquid phase. Thermally driven flow may be attributed to the vapour phase transport. The accuracy of such an approach depends, however, to a great extent on the way in which the material properties are determined and how the range of application of each of three terms in Eq. (27) is chosen. For instance a division between vapour and liquid flows does not need to be the same as the end of application of the third term. If the third term is introduced into the first one, a division between vapour and liquid transport range may become a broad transition range.

4.3 Models based upon moisture content equalization.

For the reasons mentioned previously the vapour and liquid phases are treated together and related to the same potential. They may be expressed directly by using the moisture potential, or indirectly by using the moisture content.

The following equation may be written:

$$q_m = - \left(D \frac{\partial w}{\partial x} + D_T \frac{\partial T}{\partial x}\right) \qquad (15)$$

This model is both simple, correct and easy to deal with for a homogeneous structure. Material characteristics may be easily determined provided that one is able to measure the moisture content of the material (Mahler, 1958; Krischer, 1963; Kooi, 1971). There have now been several years of experience with calculations performed using this model, in the field of soil science.

The above model covers the whole moisture content range, from entirely dry to fully saturated specimens. It requires, however, information about the moisture potential for a multilayerd structure to describe conditions at the contact surfaces.

4.4 Models based upon moisture potential.

When two materials are in contact, a condition of the potential continuity must be used. The moisture contents stabilized at contact surfaces will be quite different for various materials.

This is the main reason for using of the potential approach. This approach has also some other advantages, for example, the simplicity of expressing the boundary conditions.

The equation as follows:

$$q_m = - \left(k \frac{\partial p}{\partial x} + D_T \frac{\partial T}{\partial x}\right) \qquad (16)$$

describes the potential model, and the following material properties are used:

$$k = k(w) \quad \text{or} \quad k = k(p)$$
$$p = p(w)$$
$$D_T = D_T(w)$$

All the material characteristics are described as a function of moisture content, which means that information about the moisture content, which means that information about the moisture contents are equally necessary as information about the moisture potentials.

The approach covering both the potential and the moisture equalisation models is further analysed in the following chapter.

5 RELATIVE SUCTION MODEL FOR TEMPERATURE RANGE 274-324 K

5.1 Introduction

It is now generally accepted that the flow of moisture through porous media should be expressed quantitatively in terms of the free energy of the pore water relative to free, pure water (Nikitina, 1963, 1964; Panel Statement, 1965).

One may divide the moisture potential into the following:

- matrix or capillary potential,
- gravitational potential,
- osmotic potential,
- potential due to other forces e.g. external gas pressure.

These concepts do not require an explanation as they are well established in the field of soil science (see Appendix).

In this report the concept of suction is used instead of the moisture potential (Panel Statement, 1965; Vachaud, 1968). The value for capillary suction may be obtained by multiplication of free energy by the density of pore-water. This means that the density of water in pores is assumed as constant.

The density of pore water may be higher than the density of free water. Holliday (1966) reports the following values for cement paste:

gel water ($r \leq 2\times10^{-9}$ m) $\rho = 1100$ kg/m^3
gel and capillary water together $\rho = 1010$ kg/m^3

Gel pores are the smallest pores that are of interest and the above difference may be neglected, particularly as the micropores are only a small part of the total pore volume in building materials.

The assumption that pore-water has a constant density, excludes the analysis of the early stages of vapour adsorption. A certain amount of the adsorbed liquid layers must be present in order to justify the above assumption (see Young & Crowell, 1962, for discussion on the Frenkel-Halsey-Hill multilayer adsorption theory).

This assumption excludes also the directly variable density of water containing the entrapped air bubbles (see De Wiest, 1969, who refers to Luszczynski, 1960). In this report a pore-water has a constant density but the amount of air entrapped is variable.

Darcy's generalized law is assumed valid for the moisture contents above a certain limit if the flow is related to suction gradient and the conductivity coefficient is expressed as a function of the moisture content of the material.

For $w > w_o$ the following equation can be assumed:

$$q_m = - k (w) \text{ grad } p \qquad (28)$$

The moisture conductivity coefficient is taken to be a function of the moisture content, but is not allowed to be a function of the moisture content gradient. In practice, however, it was observed that no flow appeared until a certain pressure gradient was applied (Swartzendruber, 1963). Therefore, only this area of the moisture content field which is enclosed by the utmost drying and wetting retention curves will be considered. Moreover, in order to consider a relation between suction and water content as a single-valued function, either utmost drying or utmost wetting curves may be analysed. It will not be necessary when including hysteresis in the phenomena, for the time being, each of those two processes can be tested but only separately.

As far as simple viscous flow is concerned one may expect some deviations from Darcy's law e.g. at the very first moment of a free water-intake process, (see Philip, 1959), but basically Darcy's law can be expected to provide a good approximation to the flow phenomena, except if a pore diameter is comparable with a molecular mean free path. This gives a limit of the pore radius $r = 10^{-7}$ m, known as the boundary between micro- and macrocapillaries (Lykov, 1958).

A generalization of Darcy's law (see Richards, 1931; Childs & Collis-George, 1950; Klute, 1952; Richards, 1952; Philip, 1955, 1957; cf. Panel Statement, 1965, and Soil Water, 1972) seems adequate for our purposes (Heller, 1972; Chow & Vries, 1972), even though there are applications

where it might be less accurate. In some cases a microscopic analysis would be required, e.g. when calculating the diffusion of solutes, self-diffusion in thin films exposed to thermal, electrical and osmotic potentials, or even when calculating the unsaturated non-steady flows if the temperature gradient associated with the moisture flow is taken into account. (Soil Water, 1972, pp. 4, 29.)

A flow equation related to the suction gradient does not indicate what kind of mechanism created the flow, i.e. different driving forces are exchangable as long as the suction value remains the same.

The above hypothesis was already introduced when the moisture conductivity was assumed a reversible function of the moisture content. The density of flow rate will not be changed if the suction gradient associated with a given moisture gradient is not altered. The suction, however, represents a total suction, and consists of a few components. The ratio between these different components (matrix, osmotic, external air pressure etc) may be changed without changing their total sum. This approach is used to distinguish influence of the air on the capillary suction. Air redistribution will be later introduced as a separate part in the calculation model.

5.2 Primary and secondary mechanisms.

A specimen immersed in water, gains water at a rate which decreases with time, as shown in FIG. 19. The total water intake in a certain region is directly proportional to the square root of time. When the water front reaches the end of the specimen tha rate of water intake shows a significant change and a further increment of moisture content is very slow.

The knick point of the water intake process occurs when a continuous liquid phase covers the whole pore system and seals the free air path. Air bubbles become entrapped inside the water field and the pressure inside them is different from the atmospheric. The following conclusions are quoted from the tests of Vachaud et al. (1972):

"1. The local soil air pressure can be significantly different from

the external atmospheric pressure, e.g. + 50 milibar for rain with an intensity of 3 cm per hour or -15 milibar for gravity drainage.

2. The water flow depends not only on the boundary conditions in terms of water content and/or water pressure, but also is strongly dependent on air pressure conditions."

Air bubbles can dissolve in water but this process becomes rather slow for pores with larger radius (Bloomsburg & Corey, 1964). The time necessary to reach a full saturation may be extremly long. Künzel (1968) demonstrated that full saturation was not reached in some building materials after 3 years immersion in water. Tests reported elsewhere (Bomberg, 1971) showed the absolute saturation for the same standard gypsum reached after 2,5 months of pulsating pressure, where the pressure level was about 2×10^4 N/m^2 lower than the atmospheric one, or a few days of constant pressure level about 9×10^4 n/m^2 lower than in the atmosphere.

If air is not removed from the specimen by means of such a high vacuum, the process of air diffusion through the water phase is relatively slow. This stage of water intake process should not be treated in the same way as the first stage of capillary water intake, and the boundary between them should be determined.

The knick point discussed in Fig. 19 is reached after a few hours for certain materials, while weeks or months are needed for other materials. For this reason it can not be tested by means of a given time immersion to water as proposed by Leusden (1964) who underlined the importance of this knick point for the frost resistance.

This knick point represents such a stage of water-intake process when the water front has just reached the outer surface of the specimen i.e. water forms a continuous net and the air transfer through the specimen is just ceased. In other words this knick point represents the bubbling point, i.e. moisture content corresponding to the bubbling pressure.

Bubbling pressures for several materials were measured using a specially constructed pressure plate with a transparent bottom. Two values of pressure were observed, one during rising pressure when the first air bubble could

pass, and the other during diminishing air pressure when the last air bubble could pass. To obtain a reproducibility of measurements the tests were performed on completely saturated specimens.

For standard gypsum the following differences between the bubbling and atmospheric pressure were observed:

about 7×10^4 N/m^2 for the beginning of the air flow at rising air pressure,

about $3{,}5 \times 10^4$ N/m^2 for the end of the air flow at diminishing air pressure.

The second property is called "a backing suction of the material" (Bomberg, 1971).

With no restriction for the duration of the tests, an air bubble passing through a "saturated" specimen may be observed at different pressures.

Using another criterium for "the beginning of the air flow" all values between 3,5 and $7{,}0 \times 10^4$ N/m^2 can be measured for the standard gypsum at rising air pressure, Bubbling points having the suction level as shown by these measurements would cover a broad range of moisture contents.

Fig. 36 illustrates measurements of the limited intake rate where the above discussed knick point occurs at moisture content 190 kg/m^3, while the same specimen when tested for a free water intake produced 240 kg/m^3. K designated clay-bricks were tested in two large series. In the first, water intake was started from the hygroscopic moisture content. The end of the first wetting stage is achieved at 202 kg/m^3 (a mean value of 30 specimens). In the second test series, started at absolutely dry material, moisture content of 241 kg/m^3 was determined as the end of the first wetting stage.

Thus, both starting moisture content and the density rate of the moisture inflow to the specimen influence the division between the first and second stages of water intake process.

From the discussion on the bubbling points, it may be a concluded that the end of the first stage of the water intake occurs in a broad range of moisture contents dependently on time-scale and hysteretic conditions.

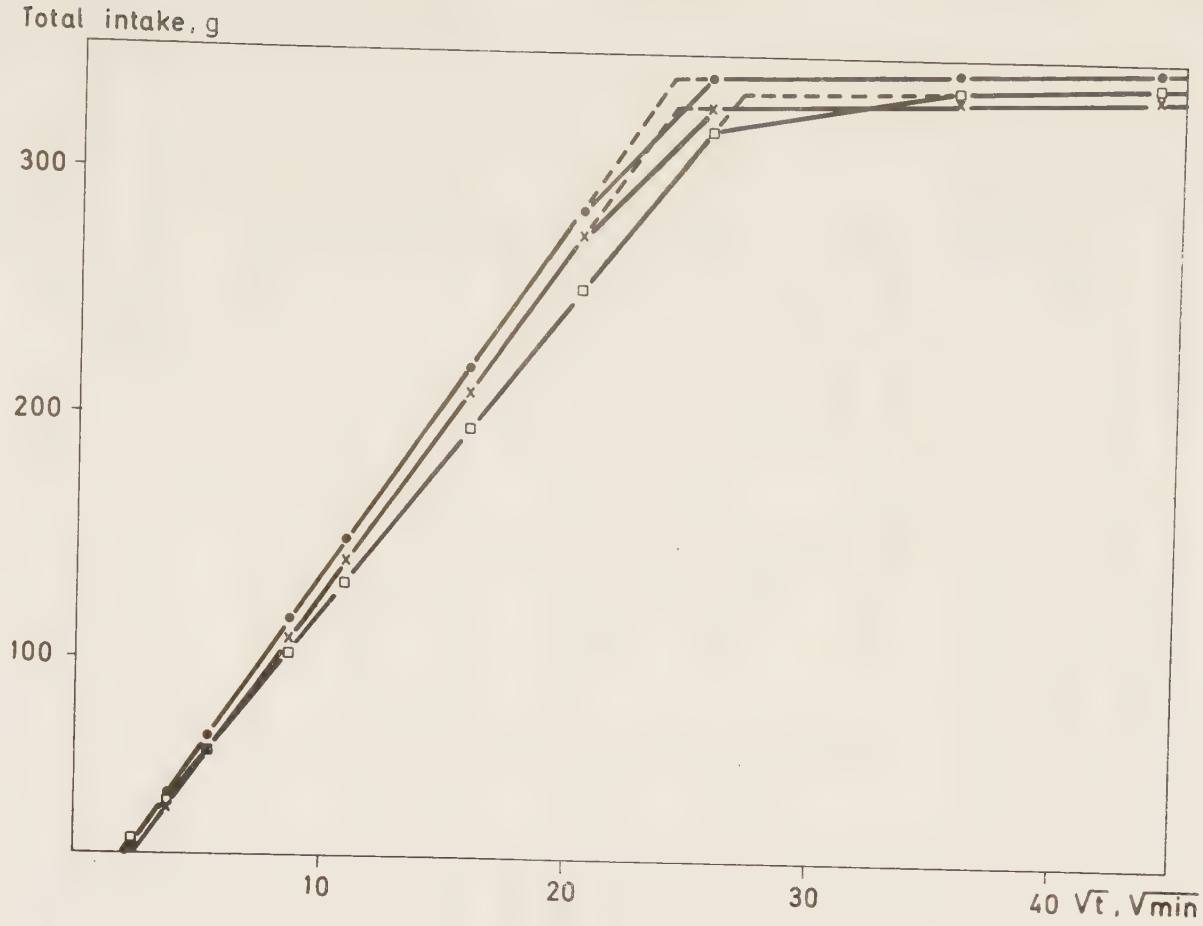


Fig. 19. Free-water intake tests of the standard gypsum specimens (density 1250 kg/m^3, open porosity 0,44 m^3/m^3).

To provide a reproducible material property a concept of capillary saturation can be introduced. It is defined as the moisture content occurring at the knick point of infiltration velocity tested under specified conditions (one dimensional water and air flow, starting moisture content equal to zero). Table 5-1 illustrates reproducibility of the capillary saturation determined for the clay-bricks.

Table 5-1. Capillary saturation against density of the specimen.

Number	Density kg/m^3	Cap. sat. kg/m^3	Number	Density kg/m^3	Cap. sat. kg/m^3
K 31	1798	237	K 41	1768	259
K 32	1796	236	K 42	1786	257
K 33	1807	248	K 43	1790	246
K 34	1887	245	K 44	1776	249
K 35	1782	244	K 45	1789	245
K 36	1785	243	K 46	1790	248
K 37	1842	199	K 47	1772	260
K 38	1840	198	K 48	1755	255
K 39	1803	235	K 49	1812	242
K 40	1789	235	K 50	1801	242

Mean values $\rho = 1799\ kg/m^3$, $w_c = 241\ kg/m^3$.

Finally, the above discussion may be concluded as follows:

(a) Different starting moisture contents or boundary conditions (e.g. expressed by the density rate of water inflow) may produce another moisture content at the end of primary flow mechanisms.

(b) The capillary saturation, which is easy to determine and reproducible property of the material, represents the end of primary flow mechanisms for a specified process of water intake.

It was required to distinguish between different stages of water intake process. The first stage of the intake process, where the flow mechnisms

are referred as the primary is basically attributed to the capillary forces. For the second stage of the water intake process, some external forces for instance pressure or temperature variations are expected to contribute. Pore air diffuses away and water fills pores and capillaries previously occupied by the air.

In order to distinguish different flow phenomena, a new concept of suction, a corrected capillary suction is introduced and defined as follows:

A corrected capillary suction is equal to an apparent (measured) suction in absence of the macroscopic air entrapment. In the range where the air blockade is present, the corrected capillary suction is equal to zero.

If moisture content is lower than the bubbling point, the corrected and the apparent capillary suction are the same.

This concept provides an approximation of the air entrapment phenomena. It is belived that the air entrapment occurs in the whole moisture content range discussed in this report (see Chapter 5.1). This assumption is based upon the research of Chahal (1964) and Morel-Seytoux (private communication) as well as on analysis of the capillary hysteresis (see Chapter 5.6).

At a low moisture content due to high energy level of the pore water, the air bubbles are quickly dissolved in the water. Air entrapment does not influence the moisture equilibria in micropores. Air entrapment is associated with the bubbling pressure determination but depending on duration of the experiments, the level of air flow density rate which determine the beginning of air transfer, the range of results may be obtained, not a single point.

The above definition of the corrected capillary suction is therefore related to the entrapment existing at the certain time i.e. may also produce different moisture contents for short or long time tests.

Practically as a boundary between primary and secondary flow mechanisms the capillary saturation is used. Above the capillary saturation the corrected capillary suction becomes zero.

5.3 Relative variables.

Material properties like suction or moisture conductivity coefficient are often shown as a relative variable, where the actual property is related to a given reference level.

The applicability of relative variables is demonstrated by Miller & Miller (1955) or even Haines (1927, 1930) who introduced "a reduced soil moisture tension". This was experimentally verified by Klute and Wilkinson (1958) and Corey and Corey (1967).

The relative conductivity coefficient (Brooks & Corey, 1964; Gardner & Millich, 1962; Vachaud, 1968) may be expressed as follows:

$$K = \frac{k}{k_{max}} \tag{29}$$

The conductivity as a function of the difference between the external and water pressures can be described as follows:

$$k = k_{max}(\Delta p)^{-m} \tag{30}$$

Eq. (30) has been known since 1936 and has been confirmed several times. It was also shown to be subjected to the hysteresis (Scheidegger, 1957). Brooks & Corey (1964) extended research of Burdine on the two media transport. Water transport and air transport are both correlated to degree of saturation. The following values of the water conductivity coefficient were postulated:

$$k = k_{max} \qquad \text{if} \qquad p_b < p_c$$

and

$$\frac{k}{k_{max}} = \left(\frac{p_c}{p_b}\right)^m \quad \text{if} \quad 0 < p_c \leq p_b \tag{31}$$

where

k_{max} = maximum of the water conductivity coefficient
p_b = bubbling pressure i.e. suction value at the bubbling point

p_c = capillary suction

Corey & Corey (1967) showed that conductivity curves of six fractions of a sand can be characterized by the same curve while using the relative variables. They conclude an existence of the following conditions of similarity:

1. geometrical similarity
2. initial and boundary conditions
3. parameter η is to be constant

$$\eta = - \frac{d(\ln K)}{d(\ln p_c)}$$

The η was called (Brooks & Corey, 1964, Laliberte et al., 1966) a pore-size distribution index and appears constant for both absorption and desorption processes (Brooks & Corey, 1964).

Two concepts of a relative moisture content are known:

(i) Degree of saturation, defined as follows:

$$S = \frac{w}{w_s} \tag{32}$$

where

w_s = maximum moisture content obtainable for the material, called the absolute saturation

(ii) Degree of effective saturation, defined as follows:

$$S_{ef} = \frac{S - S_r}{1 - S_r} \tag{33}$$

where

S_{ef} = effective saturation
S = degree of saturation
S_r = degree of saturation at the residual water content.

The residual saturation in Eq. (33) means a given hygroscopic moisture content (it is not removable by means of liquid drainage).

Brutsaert (1966) in a discussion of the probability laws for the pore-size distribution showed that the effective saturation can be calculated from the pore-size distribution index.

Finally, it may be stated that the relative variables are related to both the material and the flowing fluid and therefore may give better description of the test results than the derect variables. The influence of air on the water transport may also be approached in the similar way.

5.4 Degree of actual saturation.

As discussed in Chapter 5.2 the end of primary flow mechanisms occurs at different moisture content levels. Secondary flow mechanisms attributed with the higher moisture contents may contain other than capillary components of the moisture potential, for instance thermal or external air pressure oscillations which contribute to the air diffusion from the pore-water.

This energy may dissipate during the drying process and influence the relationship between moisture content and moisture potential.

It may be assumed that drying runs started above the capillary saturation will produce different relationship between moisture content and suction for various starting moisture contents. It may be seen in the tests of Rogers & Klute (1972).

As the energy level at the starting moisture content may differ from the capillary component a new concept is introduced, namely a degree of actual saturation. This concept relates the actual moisture content to the reference level being as follows:

(a) for drying runs, the starting moisture content

(b) for wetting runs, the capillary saturation

The degree of actual saturation is defined by Eq. (34) and Eq. (35), as follows:

$$S_{A,d} = \frac{w}{w_{os}} \tag{34}$$

where

$S_{A,d}$ = degree of actual saturation for drying
w = moisture content
w_{os} = maximum of the moisture content in the actual drying run.

$$S_{A,w} = \frac{w}{w_c} \tag{35}$$

where

$S_{A,w}$ = degree of actual saturation for wetting
w_c = capillary saturation.

Fig. 20 shows several moisture retention curves determined on standard gypsum (Bomberg, 1971). Even though the material was very homogeneous and wetting took place under similar conditions, there was a large deviation of the test results. The curves apppeared to be transformed along the moisture content scale, depending upon the starting point.

Fig. 21 shows the same retention curves but degree of actual saturation is used instead of moisture content.

Fig. 22 shows the diffusivity coefficient related to the moisture content of the specimens, and Fig. 23 presents the same data for standard gypsum but related to degree of actual saturation.

Degree of actual saturation evidently diminishes the spread of the measured values.

The drying retention curves will therefore be presented against the degree of actual saturation. As linear and semi-logarithmic scales (cf. Fig. 21) do not appear of value, the retention curves are better illustrated in a double logarithmic diagram. One uses the following formula:

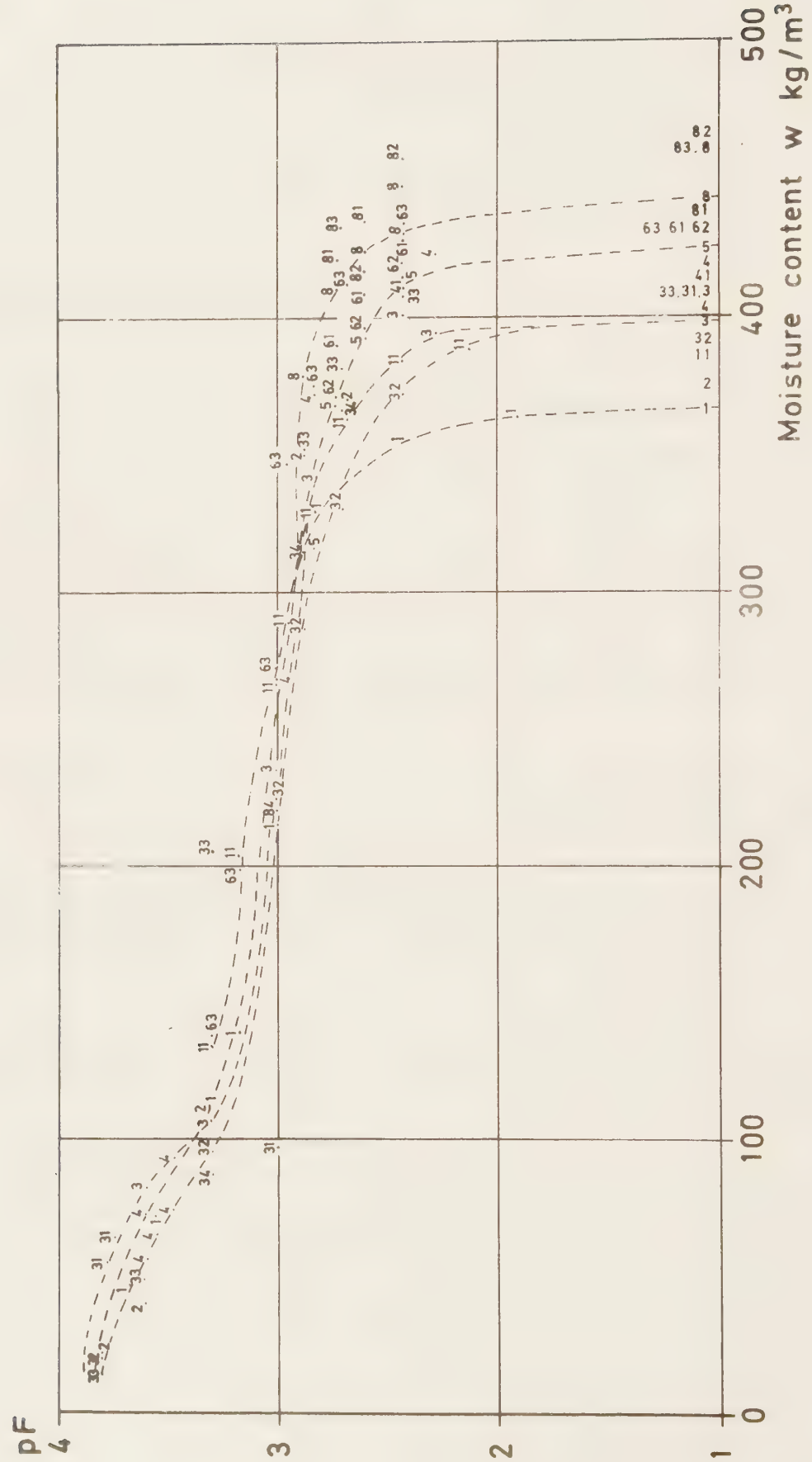


Fig. 20. Drying retention curves for the standard gypsum.

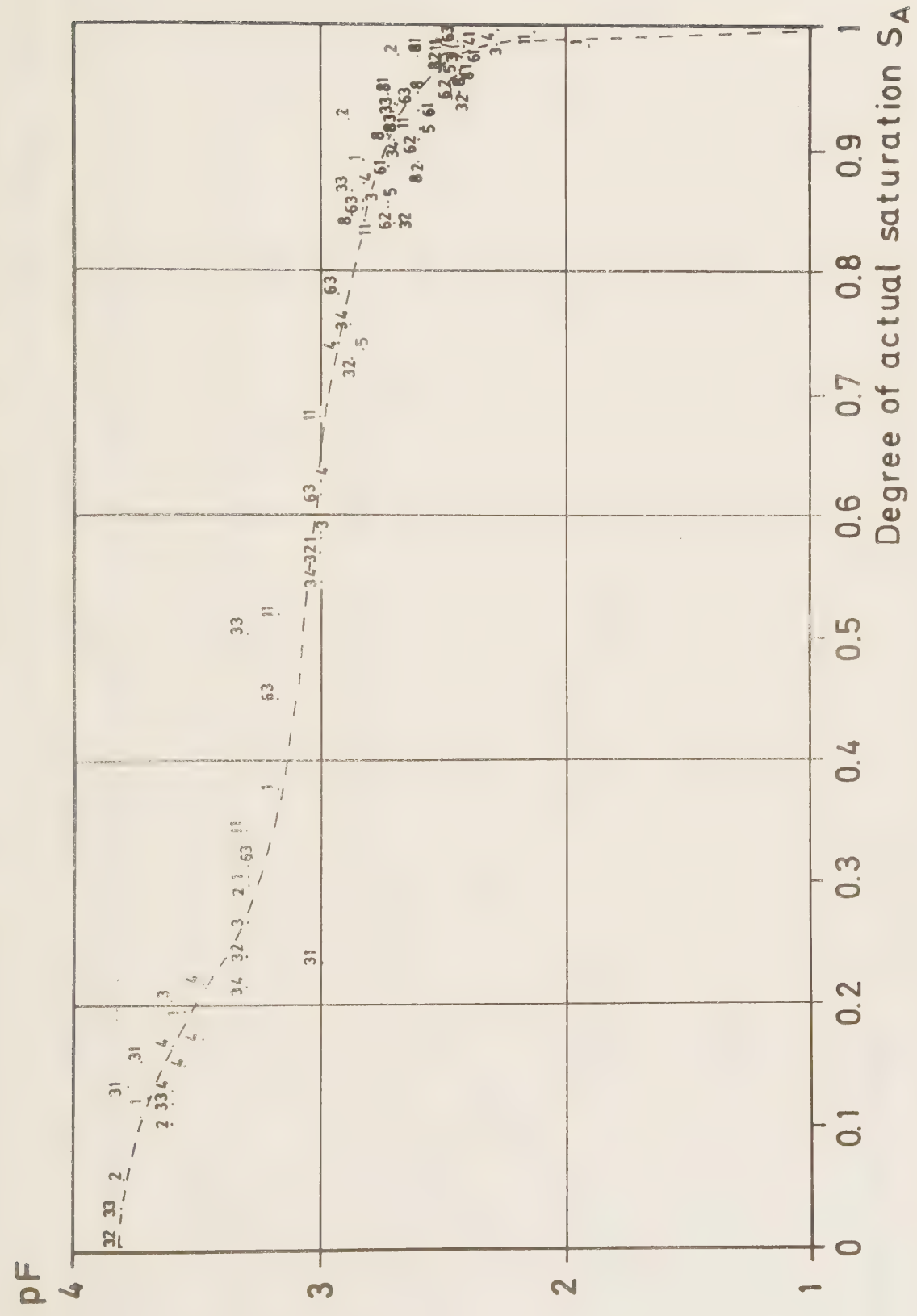


Fig. 21. Drying retention curves for the standard gypsum.

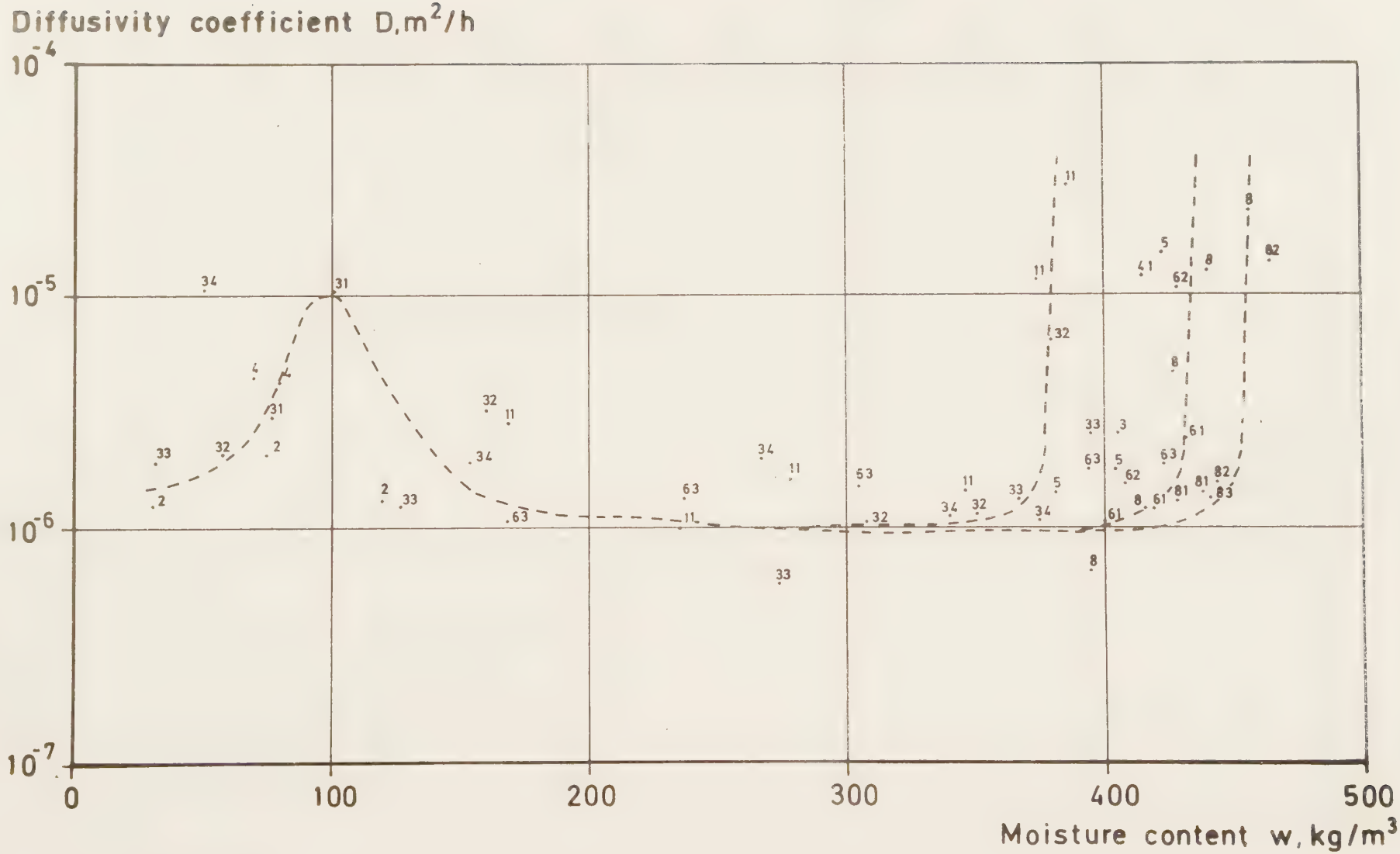


Fig. 22. Diffusivity coefficient for the standard gypsum.

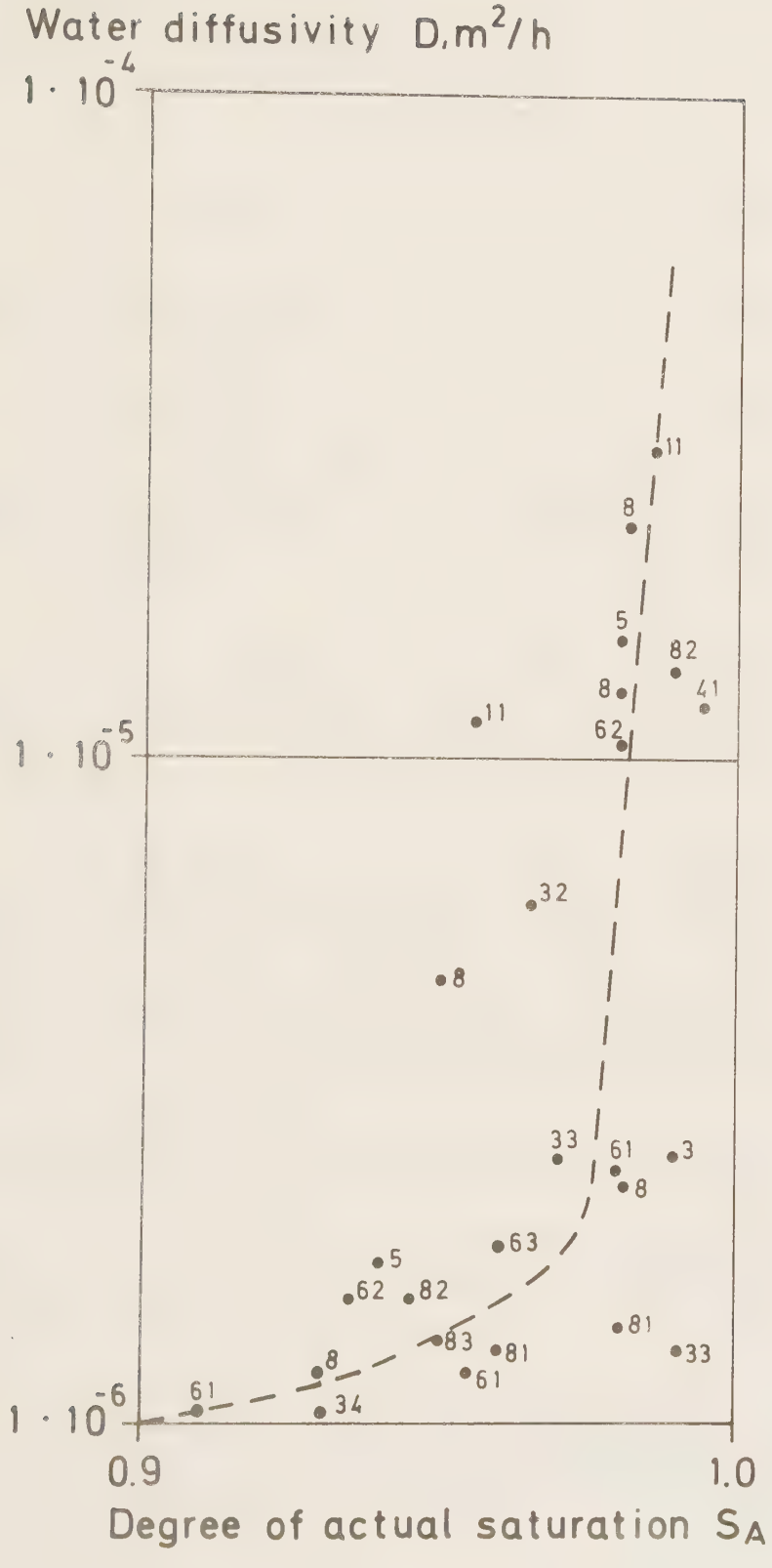


Fig. 23. Diffusivity coefficient for the standard gypsum.

$$\log p = n \log S_A \tag{36}$$

Some evidence for the usefulness of this relationship is reported by Brooks & Corey (1964), Anat et al. (1966), Laliberte et al. (1966), Brutsaert (1966), Adam & Corey (1968), Livneth et al. (1970), compare Bomberg (1972).

5.5 Hystereses.

Moistening hysteresis (associated with the wetting angle) and capillary hysteresis (associated with the shape and irregularity of the capillaries) may be distinguished.

The moistening hysteresis may be easily determined, if the capillary hysteresis and both the drying and the wetting retention curves were previously determined.

Therefore, the problem consists of predicting the other drying curves when only one drying retention curve is known, or the other wetting curves if only one wetting retention curve is known.

The independent domain theory developed by Poulovassilis (1962) and verified by Topp & Miller (1967) and Topp (1969) is based upon the concept of moisture content. As a result of discussion of the relative variables, each domain is defined by the degree of actual saturation. This is called an improved domain concept (Bomberg, 1972).

The following concepts are introduced in the improved domain concept:

a generalized suction

$$P' = \frac{p - p_o}{p_n - p_o} \tag{37}$$

and generalized degree of actual saturation

$$S'_A = \frac{w - w_o}{w_n - w_o} \tag{38}$$

where

p_o, w_o = suction and moisture content at the starting point in the drying run, or final point in the wetting run

p_n, w_n = the same variables at any characteristic point of the retention curves, providing that $w_n < w_o$.

The characteristic points of the retention curve are following:

(i) The absolute saturation.

(ii) The bubbling point, equal to the capillary saturation if the utmost drying retention curve is analysed.

(iii) The lower limit of calculations, i.e. point where the capillary hysteresis starts.

Analyses of the results of Topp & Miller (1966), Topp (1969) and Poulovassilis (1962) have illustrated two possible transformations:

(i) parallel to the suction axis, and

(ii) along the retention curve itself.

These transformations appear to be dependent upon the moisture content and suction values at the starting point, as well as on the characteristic point used in the generalized variable compared with the nearest characteristic point of the retention curve (Bomberg, 1971).

Fig. 24 shows test results of Poulovassilis (1962) and Fig. 25 show the same scanning curves recalculated into the relative variables, generalized suction and degree of actual saturation.

Experiments of Topp & Miller (1966) are shown in Fig. 26 and that of Topp (1969) in Fig. 27. Scanning curves recalculated into the generalized form show the same character for different loops, but are transformed towards each other.

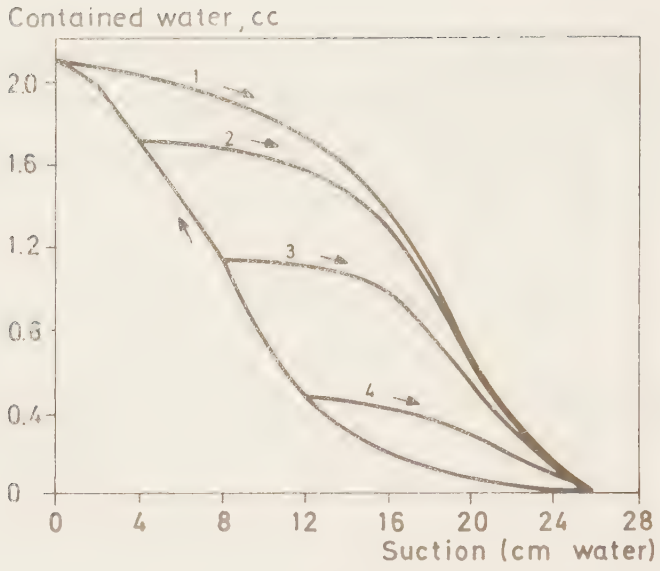


Fig. 24. Experimental primary drying scanning curves after Poulovassilis (1962) determined on the porous body of constant pore geometry prepared from glass beads.

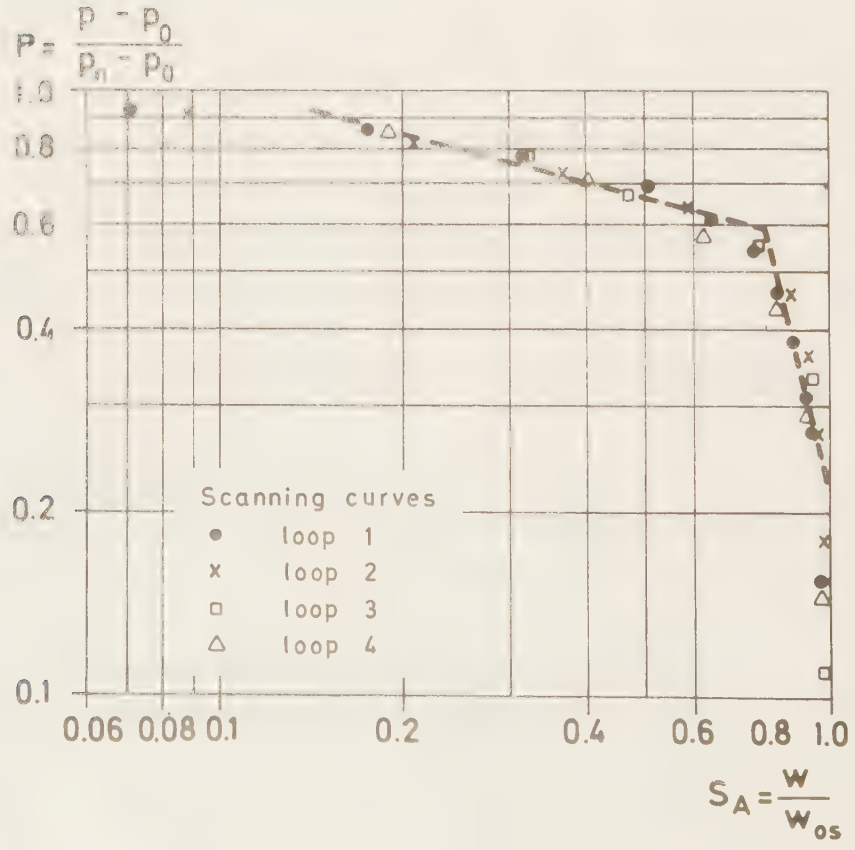


Fig. 25. Generalized drying moisture retention curve. Results of Poulovassilis (1962).

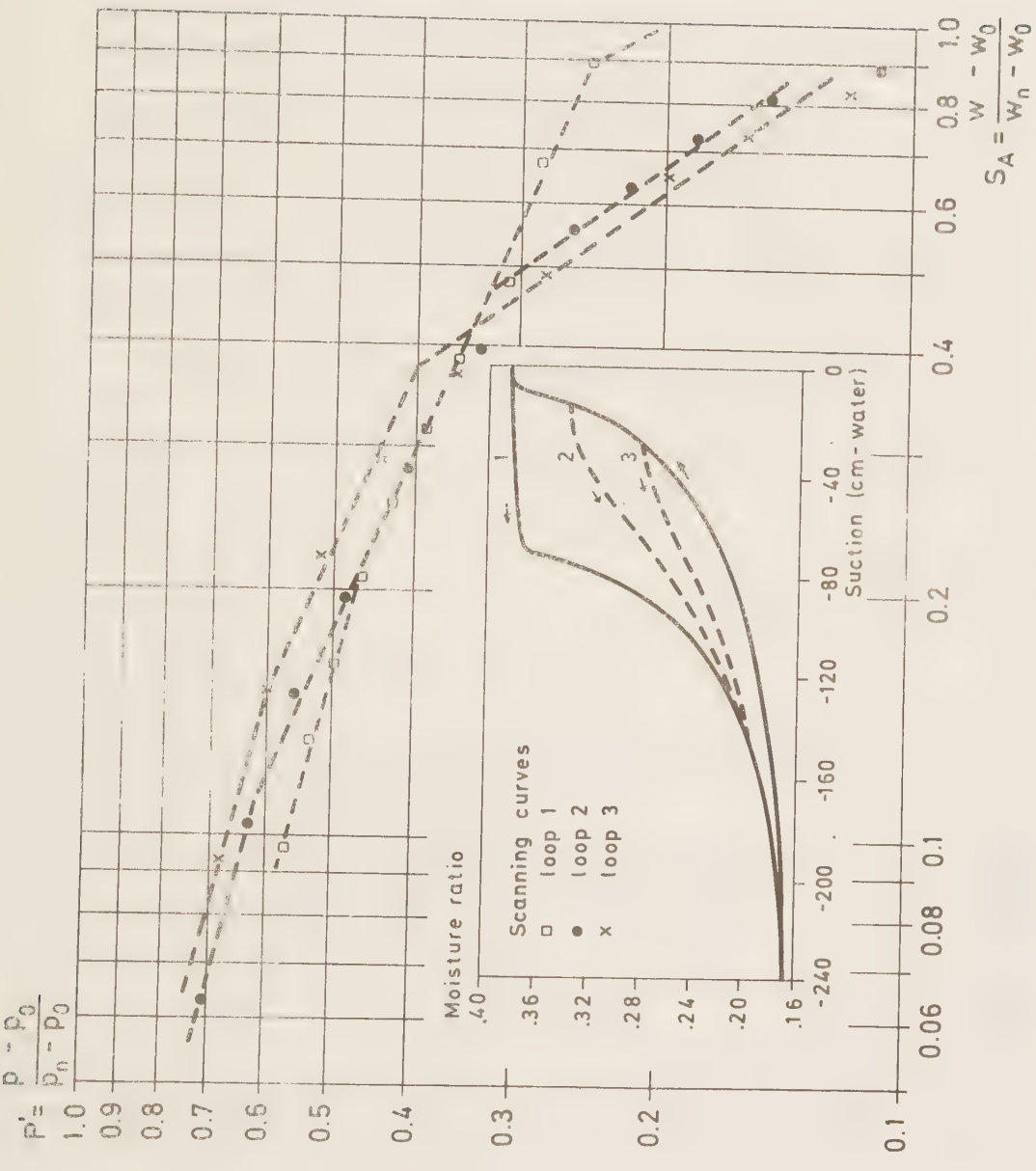


Fig. 26. Generalized drying moisture retention curve. Results of Topp (1969) determined on Rubicon sandy loam.

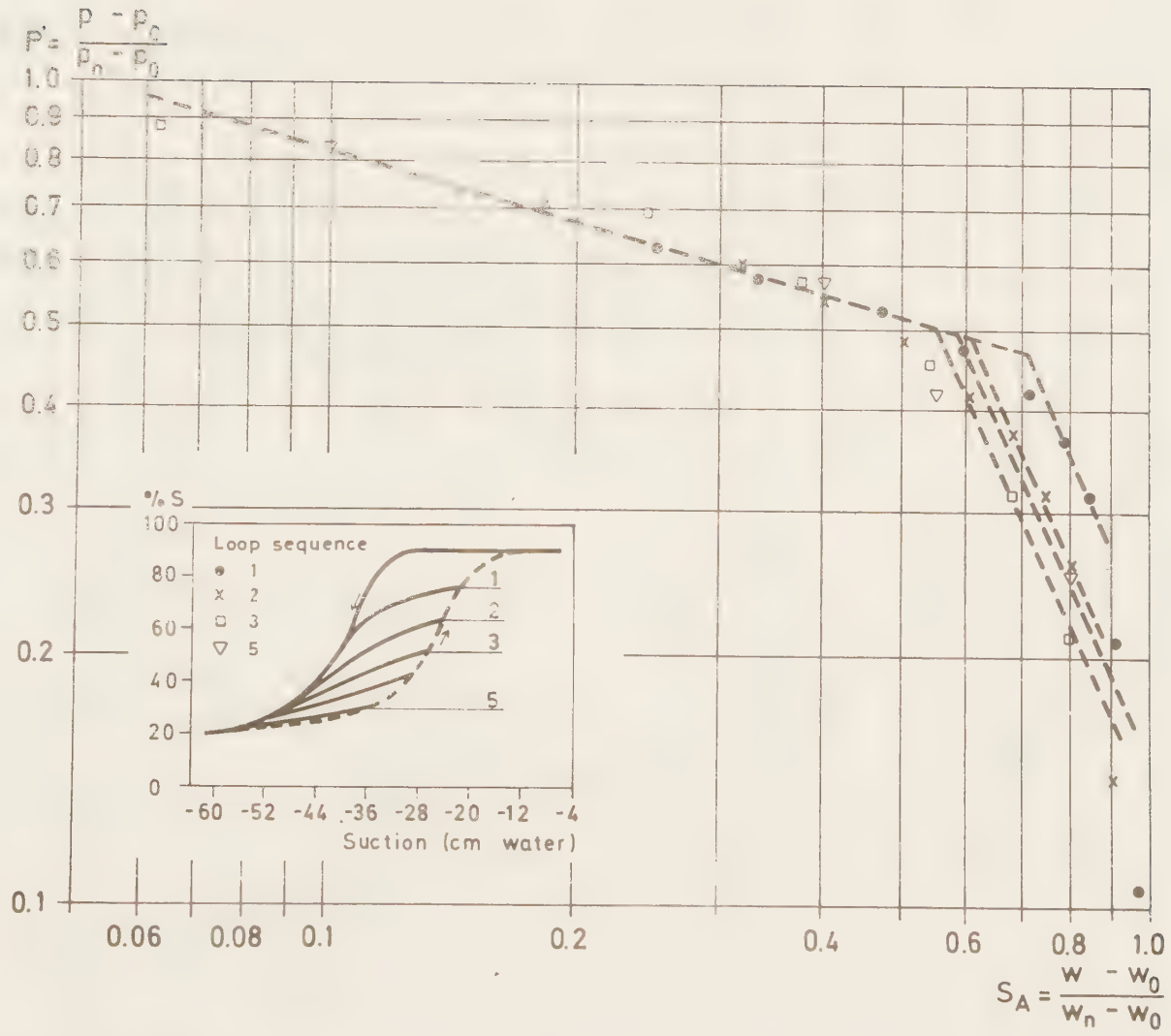


Fig. 27. Generalized drying moisture retention curve. Results of Topp & Miller (1966) determined on the aggregated glass-bead specimens.

The degree of actual saturation was used for approximative description of the drying scanning curves. It did not cover all factors necessary for description of the capillary hysteresis. The differential moisture capacity i.e. gradient to the moisture retention curve became, however, nearly single-valued function of the degree of actual saturation.

To examine a moistening hysteresis, measurements of the wetting angle were performed for some building materials.

The idea was that described by Adamson (1960): a cylindrical specimen was placed in an empty tank and water level was slowly rised until a contact between the material and the water did not create any curvature of the water surface. To check this a narrow beam of the laser light was directed on the place of contact between the material and the water.

The experiment is illustrated on Fig. 28 and Fig. 29.

The agreement between different tests was reasonably good. For standard gypsum the following values were determined:

for previously wetted, $\cos \theta = 0.787; 0.780; 0.795$
for absolutely dry, $\cos \theta = 0.65$
for drying (with water film visible), $\cos \theta = 0.97$

Series of measurements performed with bricks showed

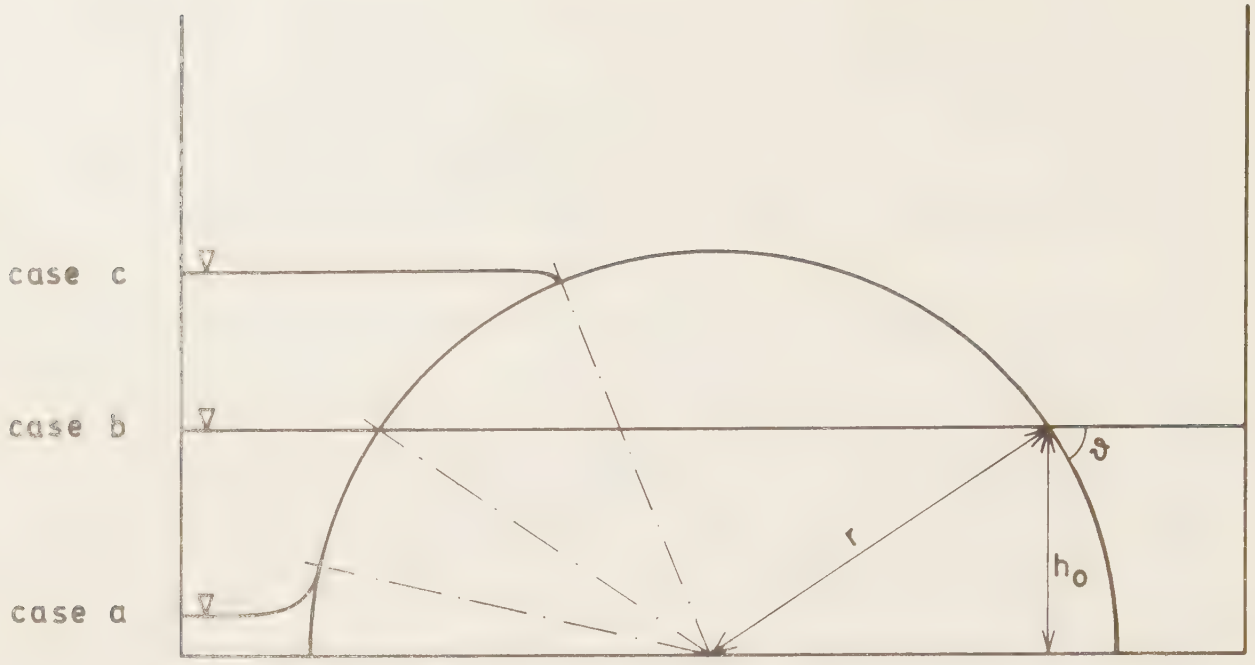
$\cos \theta = 0.61 - 0,65$ for a dry specimen
$\cos \theta = 0.73 - 0.76$ for a specimen dried at the surface but wet inside

Dry specimens of aerated concrete gave the following results:

density about 400 kg/m^3, $\cos \theta = 0.62 - 0.64$
density about 500 kg/m^3, $\cos \theta = 0.60 - 0.65$
density about 650 kg/m^3, $\cos \theta = 0.61 - 0.64$

A very quick movement of water level gave even lower results of about

$\cos \theta = 0.51$



$$\cos \vartheta = \frac{h_o}{r} - 1$$

Fig. 28 A. The idea of the wetting angle measurements, see Adamson (1960).

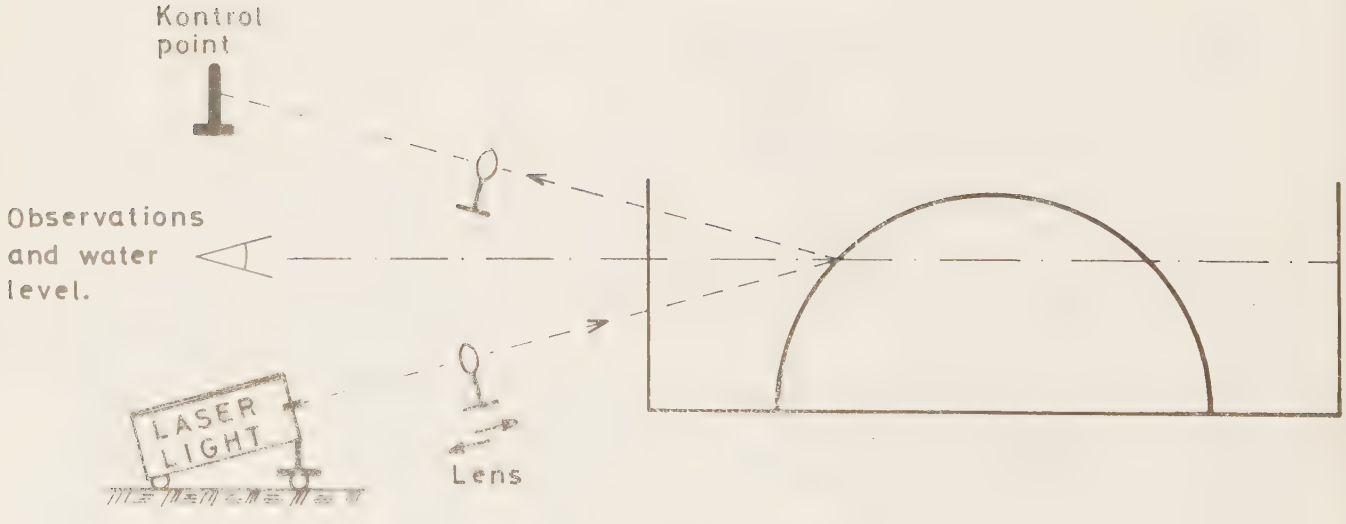


Fig. 28 B. Optical arrangement for the observations.

Fig. 29A. Measurement of the wetting angle at the moment of equilibrium.

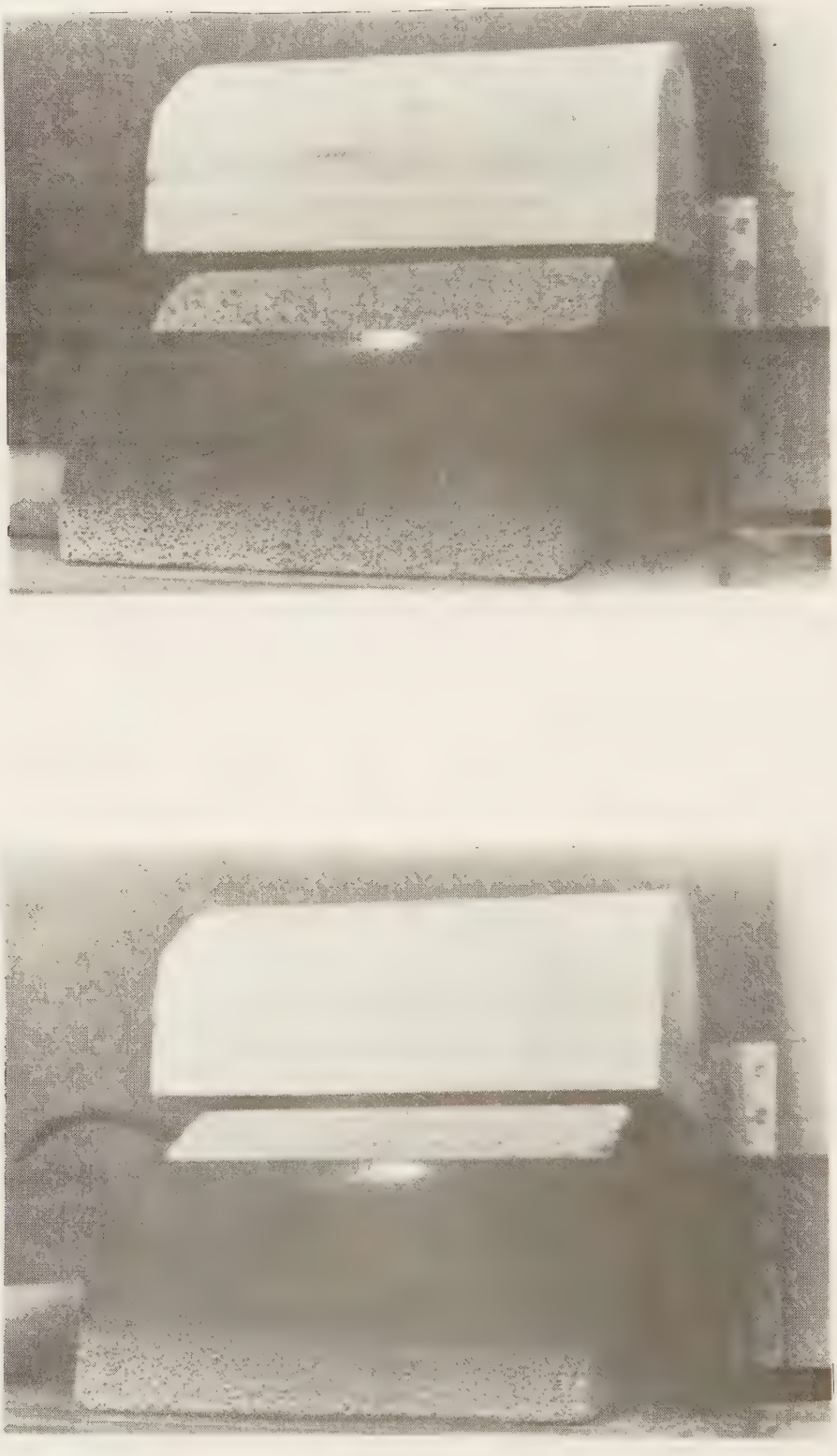


Fig. 29B. Measurements of the wetting angle when the water level is too high.

A striking similarity between measurements carried out for different materials is noted (Szelimanow, 1964, postulated $\cos \theta = 0.75$). The following values were measured:

$\cos \theta = 0.60 - 0.79$ for partly wetted materials,
$\cos \theta = 1.0$ if a film of water was present on the surface.

No general value of the cosine is assumed because of its dependence upon the degree of saturation, but the fact that in the water flow range the same magnitude of moistening hysteresis may be expected for different materials seems useful.

5.6 Simplified relative suction (SRS) model.

The following material properties must be known for calculations of moisture flow through porous materials:

(i) Moisture conductivity, or diffusivity coefficient as a function of the moisture content.
(ii) Moisture retention curve i.e. capillary suction vs moisture content
As gradient of the moisture retention curve one obtains also:
(iii) Differential moisture capacity.

The relationship between these properties may be influenced by the capillary hysteresis, and for instance capillary suction becomes a multivalued function of moisture content.

The accuracy of the calculations will therefore be affected by the chosen model of calculations.

There are two basically different patterns of calculations:

(i) Moisture flux related to suction gradient and material properties related to suction $k(p)$, $w(p)$.
(ii) Moisture flux related to moisture content gradient and material properties related to moisture content $D(w)$, $p(w)$.

The first pattern is based on a direct application of the moisture flux definition. Moisture conductivity coefficient is usually related to

capillary suction.

Relating the moisture flux to the suction gradient makes simple and reliable claculations for drying or wetting processes separately, but a transfer from one moisture retention curve to the other is difficult.

The second pattern is preferred here (see: Hanks et al, 1969) because the moisture conductivity coefficient was proved to be less influenced by the capillary hysteresis if related to moisture content or degree of saturation.

Topp (1969) concludes the review of six different tests carried out on glass-bead, sandstone, sand silt loam and sandy loam as follows: "For most purposes it appears sufficient to assume that there is no hysteresis in moisture conductivity related to moisture content".

This is illustrated in Fig. 30 quoted from Topp & Miller (1966).

Even if there is no hysteresis in the moisture conductivity coefficient the hysteresis is introduced into the moisture diffusivity coefficient which becomes a multivalued function of moisture content as shown in Fig. 1A. It happens due to the presence of hysteresis in relation between suction and moisture content i.e. under the differential moisture capacity.

Therefore, the questions most decisive for the calculation model should be formulated as follows:

(i) What is the range of moisture contents where the capillary hysteresis may not be neglected?

(ii) How to describe the influence of the conditions at the beginning of the flow on the moisture diffusivity coefficient?

The capillary saturation was already introduced as reproducible property representing the knick points of water intake where the corrected capillary suction becomes zero. This means that the highest moisture content obtainable by means of the isothermal water intake process is capillary

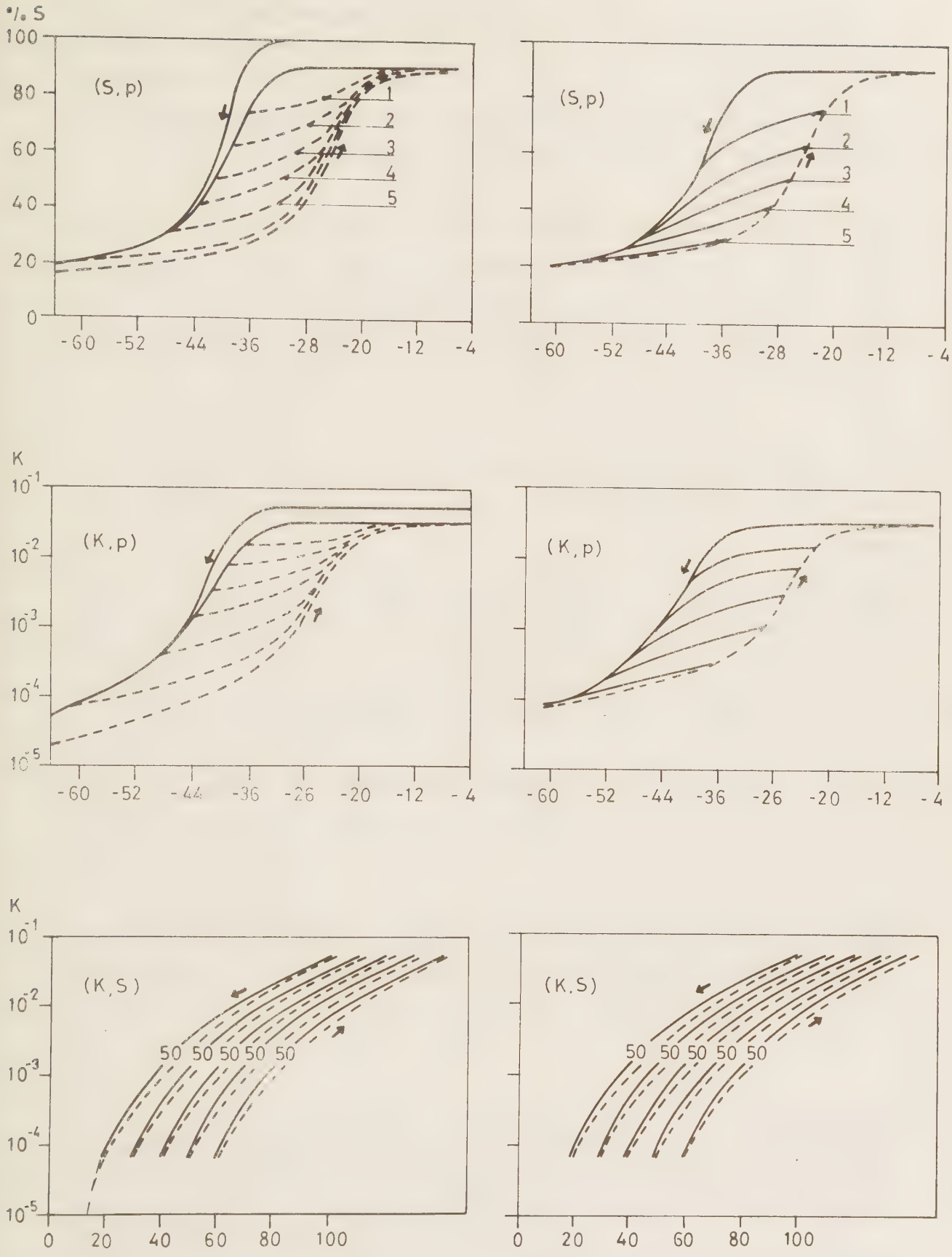


Fig. 30. Aggregated rewet / redry moisture characteristics of a glass-bead medium. From Topp & Miller (1966).

saturation. A higher moisture content may be obtained only if the material surface is exposed to water for a longer time. The surface gains water with a velocity determined by the air outflow from the specimens. Alternatively the external pressure may cause moisture inflow with a velocity higher than is determined by the air outflow.

Due to definition, the capillary saturation represents the maximum moisture content obtainable at any knick point of water intake. In a similar way knick-points of drying are treated and following research of Vos & Minnen (1966), Vos (1967), Vos & Tammes (1968, 1969) a concept of critical moisture content is used. The critical moisture content in this research is defined as follows:

The critical moisture content is equal to the minimum (obtainable at possibly low drying rate) moisture content at the first knick point of drying.

These two points are assumed to determine the range where the capillary hysteresis can not be neglected. Moisture diffusivity for moisture contents higher than capillary saturation or lower than critical moisture content is assumed not to be influenced by the capillary hysteresis.

Therefore, the diffusivity coefficient was assumed to be constant if the moisture content exceeds the capillary saturation, see curve 1 in Fig. 31A.

Isothermal moisture diffusivity (D) is expressed as a function of the substitutional moisture content, i.e. a moisture content multiplied by a correction factor as follows:

$$\text{corr} = \frac{w_s - w_o}{w_{os} - w_o} \qquad (39)$$

This correction factor is assumed to cover the main part of the capillary hysteresis and is applied for drying runs started between the capillary saturation and the critical moisture content, see curve 2 in Fig. 31A.

For drying runs started under the critical moisture content no correction need be applied, see curve 3 in Fig. 31A.

The character of the moisture diffusivity curves used in the SRS-model is shown in Fig. 31A.

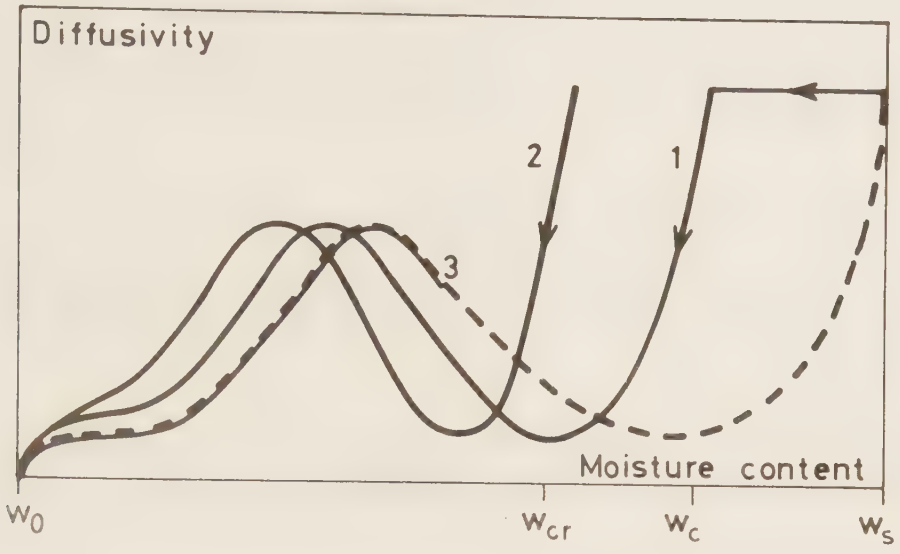


Fig. 31A. Moisture diffusivity vs actual moisture content during drying processes. The broken curve is known from the experiments. Continuous curves 1, 2, 3 are used for calculations.

The above introduced correction - ratio between the maximum and the actual range of moisture contents during drying - is based upon the concept of the degree of actual saturation (see: Figs 22, 23).

In a discussion of the wetting process, the velocity of inflow must be regarded as the decisive factor. A slow inflow of moisture (either vapour or limited rain supply) allows for evaporation and condensation processes. Moisture is located in the smallest pores and capillaries in front of the slowly advancing front of water. Moisture content distribution forms a profile with relatively little slope over the whole thickness of the material, which slowly moves forewards.

A quick inflow of moisture, e.g. free water intake, causes a sharp difference between an area with the capillary saturation close to the inflow surface, and the relatively dry remaining material. Free paths of air outflow are broken already at the early stages of infiltration and air entrapment may be attributed to quite a low mean value of moisture content. Due to a steep gradient of moisture, the air is compressed to a degree exceeding the bubbling pressure and the air outflow takes place

as long as the moisture content is lower than the capillary saturation.

Both quick and slow wetting will produce the same effect, namely complete the capillary saturation. Air entrapment, which is different in both cases, cases, may, however, cause a difference in the time necessary to reach the capillary saturation.

In the SRS-model, two extreme cases of air entrapment are used:

(i) Air entrapment occurs at the critical moisture content in case of the free water intake.

(ii) Air entrapment occurs at the capillary saturation in case of the limited water intake or the capillary condensation of water vapour.

Moisture diffusivity for these cases is shown in Fig. 31B.

In the SRS model, the moisture diffusivity is assumed multi-valued function of moisture content as shown in Fig. 31A for drying, and Fig. 31B for wetting processes.

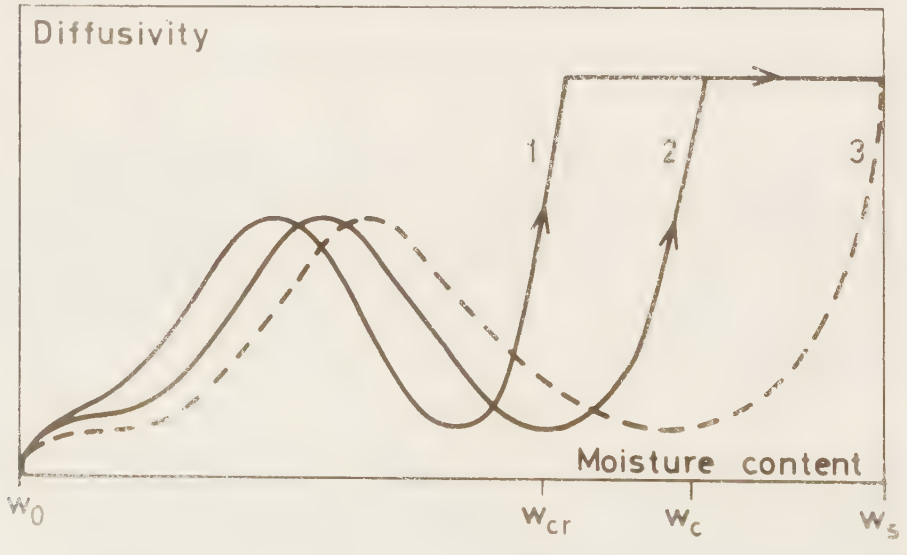


Fig. 31B. Moisture diffusivity during wetting: 1. free water intake
2. capillary condensation or limited water intakes
3. known from the drying experiments.

The following simplifications were introduced into moisture diffusivity coefficient:

(a) Drying started from a moisture content higher than the capillary saturation was treated similarly to a slow wetting, i.e. constant diffusivity was assumed if the moisture content exceeded the capillary saturation.

(b) The maximum level of diffusivity coefficient was not decreased for all drying processes started between capillary saturation and critical moisture content.

(c) Air blockades occurring during wetting with an intermediate velocity of moisture inflow were omitted, i.e. only two curves are discussed in Fig. 31B.

Thermal moisture diffusivity i.e. moisture diffusivity related to temperature gradients (D_T) is discussed in Chapter 3.2 and calculated according to Eq. (23).

Even though the calculations are carried out entirely in terms of moisture content, knowledge of suction is also necessary. Suction is used for a contact plane between two materials and the boundary conditions.

Finally the outline of the SRS-model is given in Fig. 31C.

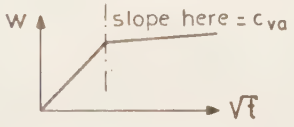
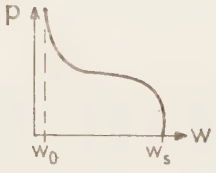
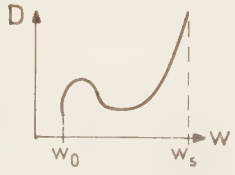
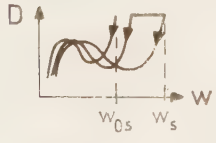
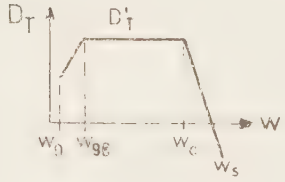
Desorption		See also
Basic equation	$\frac{\partial w}{\partial t} = \frac{\partial}{\partial x}\left(-D \frac{\partial w}{\partial x}\right) + \frac{\partial}{\partial x}\left(-D_T \frac{\partial T}{\partial x}\right)$	Eq (15)
Boundary cond.	for $w < w_c$ $\quad w = w(p)$ for $w \geq w_c$ $\quad w = w_c + w_A$	§ 4.4
	p = capillary suction (apparent)	§ 5.2
	w_c = moist. cont. at the capillary saturation	§ 5.2
Second stage of water intake (an exemple of the secondary flow mechanism)	$w_A = c_{va}\sqrt{t}$ 	Fig 19
Material properties as tested during drying run	 	Figs 3, 6, 8 Figs 20, 21 Figs 14, 15 Figs 22, 23
Control of the tests in double-log plot		Figs 63, 64 Figs 65, 66
	$S = \frac{w}{w_s}$ or $S_A = \frac{w}{w_{os}}$ if $w_{os} < w_s$	§ 5.4
Moisture diffusivity during calculations		Fig 31 A Fig 31 B
Thermal diffusivity	$D(S_A) \longrightarrow D(w)$ correction factor	Eq (39)
	$D'_T = D_T(T, \delta_n)$	Eq (23)
	δ_n = vapour permeability (WVT)	Eq (19), (22)
		Fig 18
Other mat properties. Known from the tests	w_{98} = equilibrium at $\varphi = 0.98$ or w_{cr}	§ 7.2
	w_{cr} = critical moisture content	§ 6.4
	w_c = as above	§ 7.1.1
	w_s = absolute saturation	§ 7.1.2
	δ_n = as above	§ 7.1.4

Fig. 31 C. The outline of the SRS-model.

6 COMPARISON BETWEEN TESTS AND CALCULAITONS WITH THE SRS-MODEL.

In order to exemplify the SRS-model introduced in Chapter 5 it is formulated for computations in Chapter 6.1 and the results of a few computations are reviewed in Chapter 6.3-6.6. They are compared with experiments performed on two building materials: aerated concrete and clay-bricks which are described with regard to moisture properties in Chapter 6.2.

6.1 Description of the program.

The program is developed on the basis of Kooi (1971) and Sandberg (1973). It is written in Fortran and concerns one-dimensional heat and moisture transfer.

Material properties and climate data are gathered in arrays where the subscripts are either moisture content or time. Steps in moisture content may be equal to any natural number e.g. 1 kg/m^3 and the time steps in arrays are equal to 24 hours.

There are following arrays of material data: moisture content, capillary suction, moisture diffusivity, thermal moisture diffusivity and heat conductivity. All the material properties are related to the number of steps necessary to obtain this moisture content to which the property is ascribed.

There are following arrays of climate data: outside and inside air temperature, outside and inside vapour concentrations, all related to the number of days in a sequence from January the first.

Additionally, an array containing days with rain and raining time in seconds is given in the form of a direct input.

Conditions of heat and mass-transfer at the material surface for both dry and rain periods including the maximum rain intensity are also given by the input data.

Two kinds of boundary conditions are used in the program: a dry climate and driving rain conditions.

A dry climate, evaluated as constant for a period of 24 hours, is calculated on the base of twelve months values recorded in the input cards. That means, the shortest time period used for the description of boundary conditions (except rain time) is 24 hours. This period may be extended as required.

The moisture content field is calculated with automatically chosen time steps for the whole time when the boundary conditions are constant. When the required time has passed, the new set of boundary conditions is automatically chosen on the base of the mean day-temperature recorded in the input data.

When it rains the inflow is calculated by means of a mean value of diffusivity at the surface and the first calculational point i.e. in the middle of the first layer. The moisture content at the surface becomes instantaneously equal to the capillary saturation, and the cumulative raining time introduces the correction factor proportional to the square root of time.

Inflow to the first layer is compared with the given rain intensity and decreased to its limiting value if it exceeds the water supply.

In the opposite case if the water supply is larger than the calculated inflow, nothing is done. For free water intake tests it is therefore sufficient to put the limiting rain intensity adequately high.

In a "dry" climate, the vapour concentrations in the environmental air and at the material surface are calculated from values of suction (with regard to temperature, moisture content etc.). The inflow or outflow is obtained as a difference in vapour concentration multiplied by the surface vapour transfer coefficient.

Computations are to a certain extent automatically adjusted. Time steps are chosen by the computer with regard to the mean moisture content, reverse slope of the moisture content distribution, changes in the boundary conditions etc.. Time steps are required to fall within a certain a certain range of the stability conditions, providing at the same a short running time.

Diffusivity coefficient used for claculations are related to the mean points both in space and time steps, i.e. we calculate the expected value on the base changes in the previous time step (cf. Hanks & Bowers, 1962).

The output information is given for each beginning and end of a rain period plus, at the required frequency, e.g. each hour for rain, each week for drying conditions. It is given in the form of the drying/wetting rate and moisture content distribution.

The program is listed in the appendix.

6.2 Materials tested.

When information about both diffusivity and retention curves is required, the choice of material becomes very limited. The only building material sufficiently described in technical literature in this respect appears to be aerated concrete.

Both moisture retention and diffusivity curves are taken from Kooi (1971). The moisture retention curve was determined partly by recalculation of the sorption isotherms and partly by means of a pressure plate technique at the Agricultural University at Wageningen, Holland. The diffusivity curve was taken in the uncorrected form, directly from the drying experiments. Additional informations about this material was taken from Vos (1967), who tested a similar product.

Another material which will be discussed here, is a clay-brick designated K-brick. In order to throw some light on the determination of the diffusivity curve, test regarding this material are reported in detail.

Two test series were performed in order to provide moisture-content distributions as a function of the time at known boundary conditions.

The specimens in the first series were allowed to absorb water for a given time and were later insulated on all sides. A moisture equalisation process was started and after a period of time the specimen was cut into six pieces (by means of a special guillotine) and the moisture content distribution was determined. The specimens had dimensions of about 245×65×40 mm.

The second series was carried out in a similar way, except that one surface was exposed to air. The amount of moisture lost was registered. Originally the water was supplied from both ends of the specimens in a vacuum chamber and a distribution of moisture at the beginning of these tests was v-formed (see Table 6:2).

Tab. 6.1. Moisture content in kg/m^3 in the moisture equalisation tests.

Specimen number	Time (hours)	Moisture content in layers (cm) 0-4	4-8	8-12	12-16	16-20	20-24	Mean 0-24
1	20	118	60	3	2	0	2	31
2	45	118	73	23	1	2	2	36
3	45	95	46	9	1	1	2	26
4	141.5	86	50	26	1	1	1	28
11	314	92	61	37	20	1	1	35
12	473.5	78	54	30	9	1	1	29
13	625	67	48	28	7	2	2	26

Tab. 6.2. Moisture content in kg/m^3 in the one-side drying tests.

Specimen number	Time (hours)	Moisture content in layers (cm) 0-4	4-8	8-12	12-16	16-20	20-24	Mean 0-24
15	24.5	217	209	145	129	179	236	186
16	121	193	186	160	142	191	196	178
17	293.5	119	115	86	86	125	142	112
18	453	110	107	88	84	122	129	107
19	625	95	96	85	82	109	101	95
20	846	75	82	62	56	79	80	72
22	1197	66	68	57	62	76	82	68

Tab. 6.3. Mean moisture content in kg/m^3 in the one-side drying tests.

Time (hours)	Moisture content of the specimen numbered						
	15	16	17	18	19	20	22
0	201	227	181	180	183	151	180
24.5	191	217	170	170	175	142	170
121		180	137	137	136	114	136
222.5			125	127	121	104	124
293.5			115	121	113	97	116
381.5				115	108	92	109
453				111	103	88	104
625					96	81	96
846						73	88
1197							70

Moisture diffusivity coefficient was calculated for two tests series as presented in Table 6.1 and 6.2. The latter deals with drying from an initial level higher than the critical moisture content. This means that a correction factor for a substitutional moisture content need to be introduced. Instead of real moisture contents, the substitutional moisture content is shown against the diffusivity coefficient in Fig. 32.

Moisture equalisation tests are not recalculated as the process of wetting does not require any correction.

Diffusivity coefficient calculations as shown in Fig. 32 are far from being accurate; moreover the diffusivity is not determined for very high or very low moisture content ranges. Some help may be obtained from dry-cup permeability measurements and water infiltration measurements. Three different approximations of the diffusivity curve, are shown in Fig. 32 where alternative C gives the best fit to the drying tests.

Fig. 33 shows a drying retention curve determined for this material by means of a sorption balance and a pressure plate.

Fig. 34 shows drying under laboratory conditions. The calculations are carried out for three D-coefficients as shown in Fig. 32. Mean moisture content as a function of time shown in Fig. 34 does not differ very much between all three alternative D-curves.

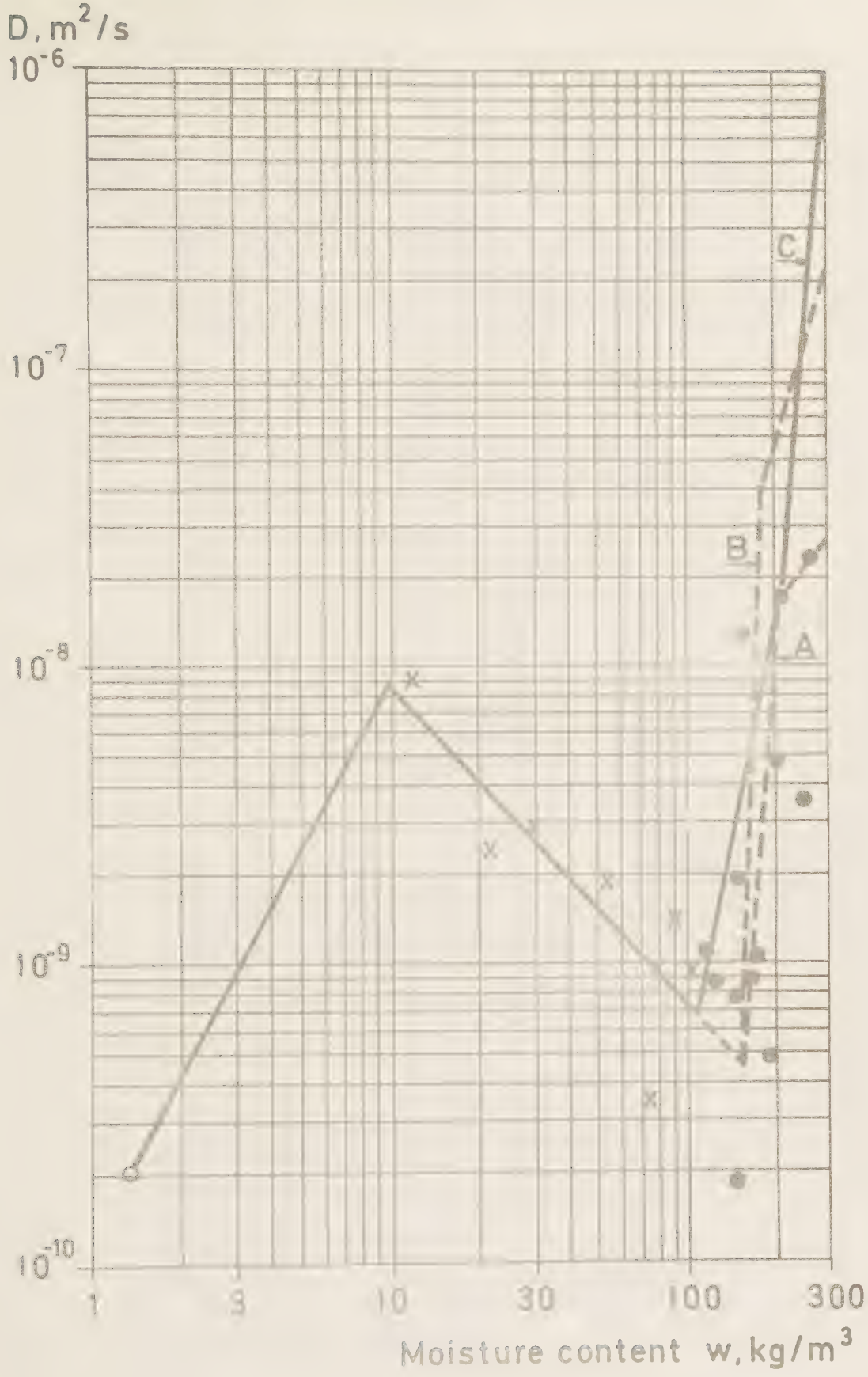


Fig. 32. Diffusivity of clay-bricks (sort K) determined as follows:
● drying from about 180 kg/m^3 and recalculated to 300 kg/m^3
× wetting during moisture equalisation process
Three possible assumptions A, B, C where C is used for the following calculations. Average density 800 kg/m^3, open porosity 0.3 m^3/m^3

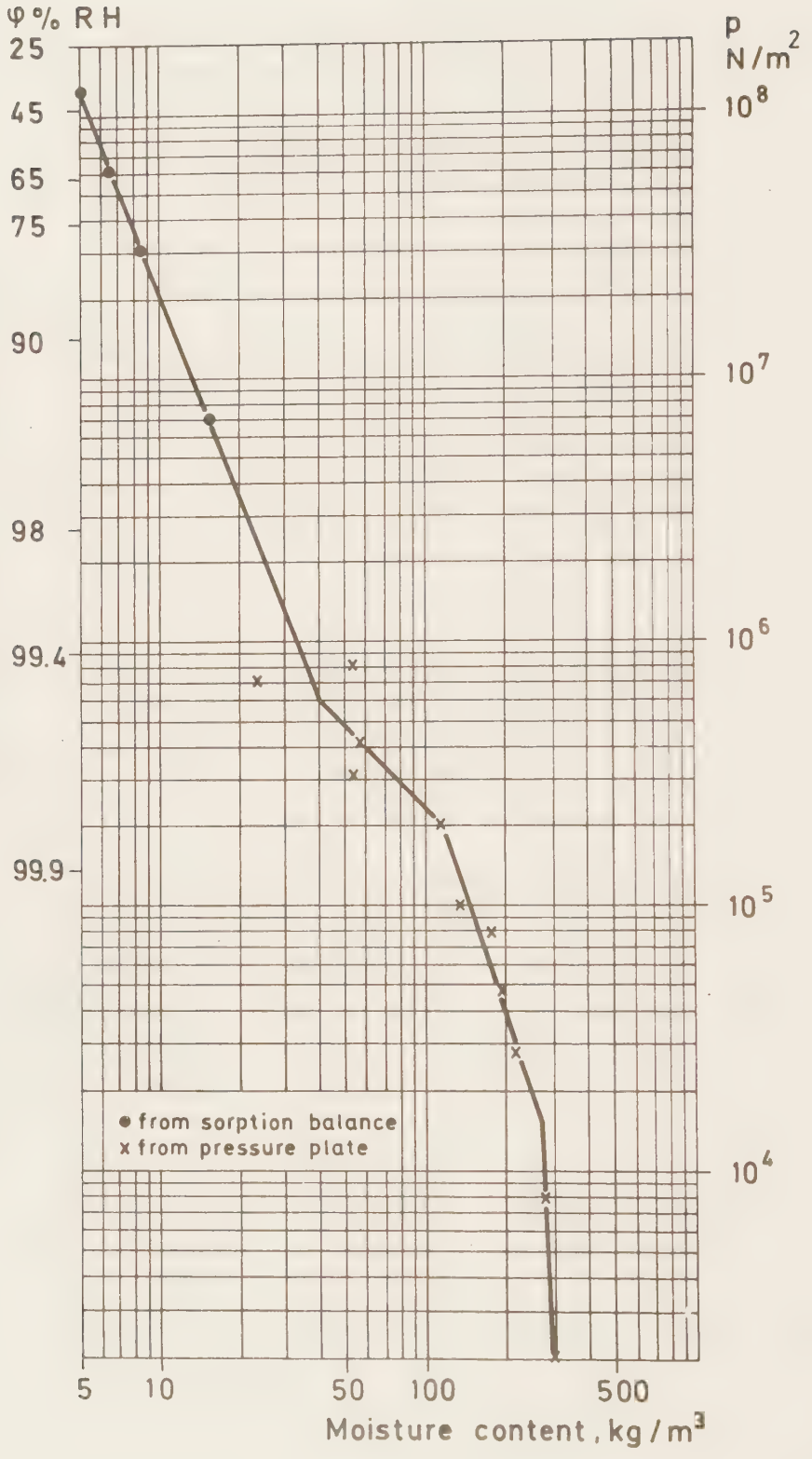


Fig. 33. Drying retention curve for the K-sort of the clay-bricks. The material has density about 1800 kg/m^3, and open porosity 0,30 m^3/m^3.

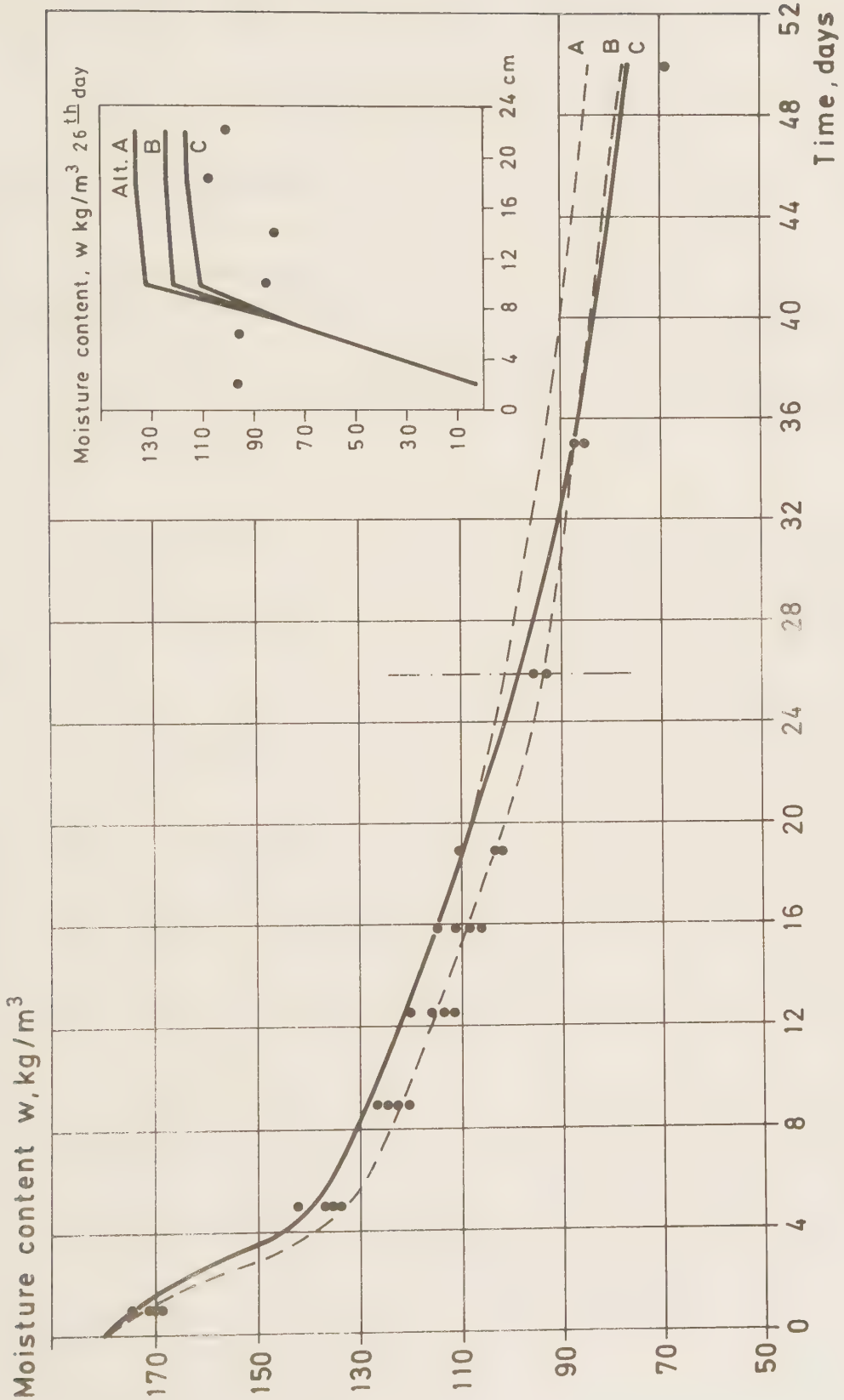


Fig. 34. Mean moisture content and moisture content distribution during one-side drying of the clay-bricks with diffusivity coefficient taken as shown in Fig. 32. Calculations performed with a preliminary version of the program (see Chapter 6.4).

This fact is really important. It means that as far as the mean moisture content is concerned, the same drying curve may be claculated with a number of different combinations of the material properties and the boundary conditions. Note that the calculations presented in Fig. 34 were carried out using the same surface coefficient of mass-transfer, and by changing this coefficient the drying curve may also be altered.

One more point should be emphasized while discussing Fig. 34. The results shown there consist of four specimens with an initial moisture content of about 180 kg/m^3 and three with quite different starting moisture contents (151, 201, 227 kg/m^3). Moisture content distributions were recalculated by means of the degree of actual saturation so that a mean initial moisture content was equal to 180 kg/m^3. All points appear to follow the same curve.

6.3 Water intake process.

Free water intake was tested on the K-bricks with a mean density 1799 kg/m^3. Measuring procedure for these tests is described in Chapter 7.1.

Fig. 35 shows two different water intake measurements, where one represents a mean value for twenty tested specimens, the other a minimum of these twenty tests. Against these measurements the following calculations are shown:

(i) According to the SRS-model, with a corrected diffusivity

(ii) As above, but with a non-corrected diffusivity, i.e. diffusivity as a function of moisture content is the same for wetting and for drying process.

If a free water film exists on the material surface, the calculated inflow to the first layer of the material is assumed to be independent of the moisture content and equal to the maximum obtainable for the given material. This simplification can be observed in the first period (1.5 hour) of the calculated intake process. It causes too high intake during the early stages of infiltration.

Fig. 36 shows calculated and measured water intake process for clay-bricks exposed to driving rain with intensity 0,25 kg/m^2 h. Calculations headed 1 and 2 corresponds to diffusivity curves 1 and 3 in Fig. 31B i.e. show the extreme cases of maximum and minimum of the air entrapment. Calculations of the limited water supply are carried out with the intermediate curve 2 in Fig. 31B.

Fig. 37 shows the free water intake test for aerated concrete. Calculations were based upon the material properties determined during drying tests performed in Holland (Kooi, 1971) and compared with experiments on the wetting of a Swedish product (Fagerlund, 1971). Fig. 37 clearly shows how small is the correlation between the moisture characteristics and density of the specimen.

Finally the agreement between the measured and calculated wetting processes is considered as satisfactory, particularly because the diffusivity coefficients used in the above c alculations were determined in the drying experiments.

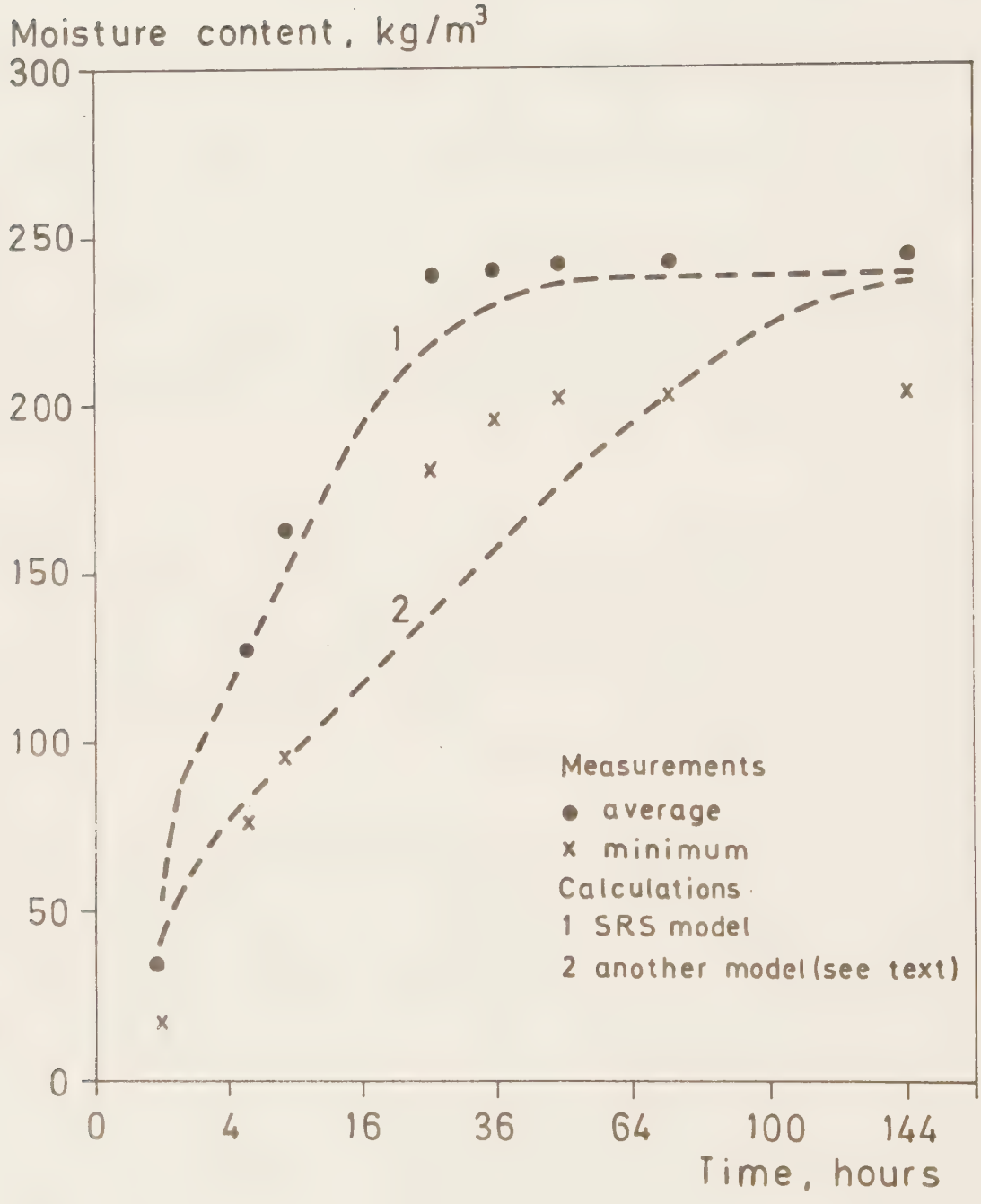


Fig. 35. Calculated and measured free-water intake for the clay-bricks. In the SRS-model diffusivity is a function of a degree of saturation. In the other calculation diffusivity is the function of moisture content as determined during drying tests.

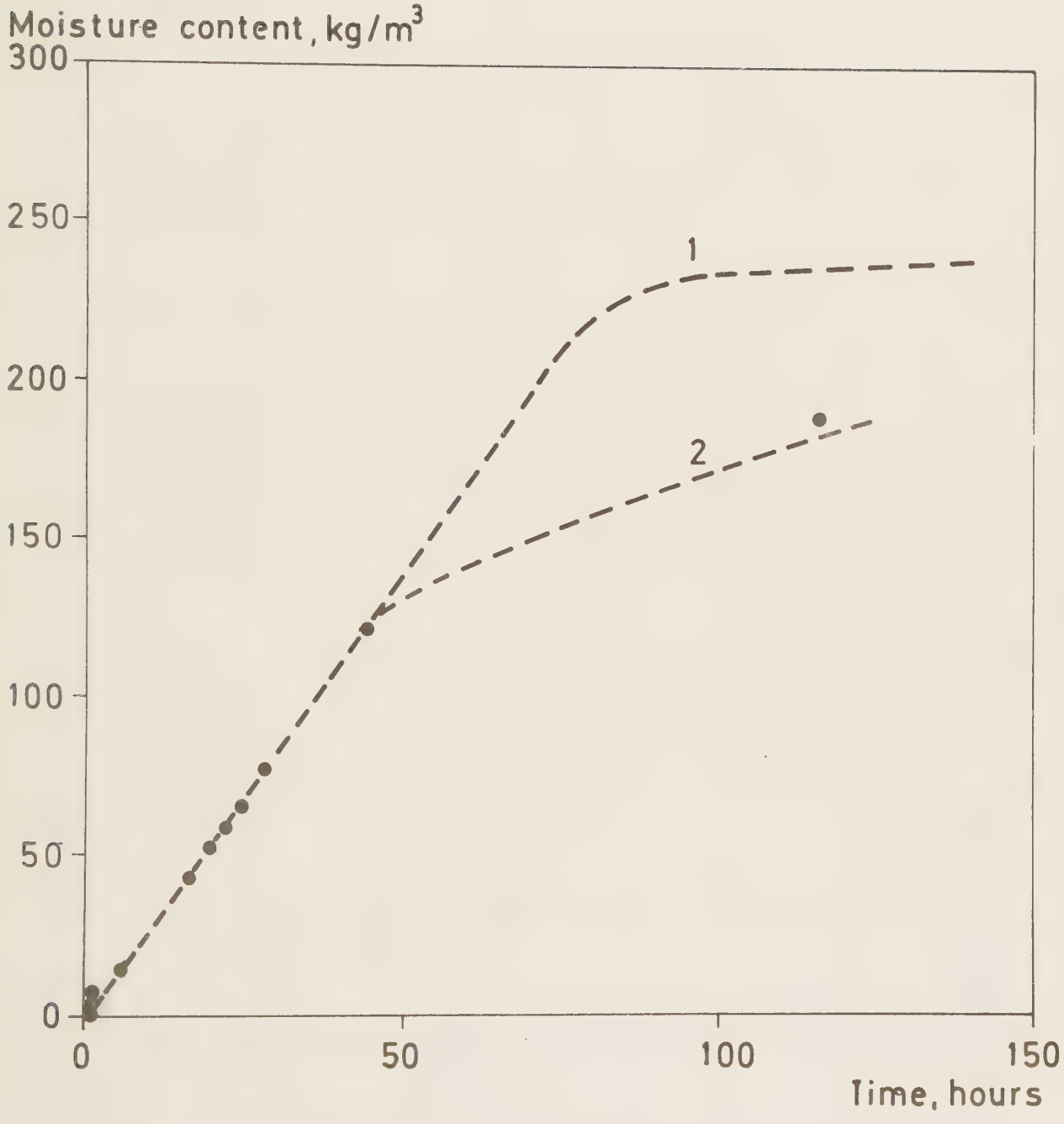


Fig. 36. Calculated and measured water intake for rain with intensity 0,25 kg/m^2 h, see text.

Fig. 37. Water intake of aerated concrete. Measurements performed on a material with density 500 kg/m^3 and open porosity 0,78 m^3/m^3, calculations were based upon drying tests of Kooi (1971) where the material had ρ = 700 kg/m^3 and the open porosity 0,70 m^3/m^3.

6.4 Thermally driven flows.

Fig. 38 presents measurements and calculations relating to the aerated concrete roof tested by Vos (1967). Capillary saturation is not known for this sort of the aerated concrete. Calculations were carried out for the following assumptions:

$w_c = 295$ kg/m^3 and $w_c = 335$ kg/m^3 (see Fig. 9).

It is seen in Fig. 38 how the level of the capillary saturation influence the diffusivity curve and in turn equilibrium obtained between moisture equalisation and thermally driven flows.

Calculation shown in Fig. 39 and Fig. 40 were carried out for two cases:

(i) Thermal moisture diffusivity was assumed constant in the hygroscopic range.

(ii) Thermal moisture diffusivity was assumed variable. As only the dry-cup vapour permeability was known, the dependence D_T on moisture content was assumed to be as discussed in Chapter 3.2.

The agreement between test and calculation is good for high moisture contents (Fig. 38) but not so good for tests accounting the hygroscopic range (Fig. 40). The same will be seen later in Fig. 43 and 44. For the same reason Kooi (1972) himself did not use the measured but a "corrected" material property.

Fig. 41 presents measurements of Hanson (1957), where exceptionally steep gradient of temperature was applied.

The final moisture distribution is shown in Fig. 41 against the measured values, while Fig. 42 shows calculated moisture distributions after 20, 50, 100, 150 and 300 days of the tests.

The above measurements of moisture content distributions were performed with the specimens sealed on all sides except one. In contradiction to these tests, Lund-Hansen (1967) tested aerated concrete exposed to air at the both ends and recorded all the climatic conditions as well as the

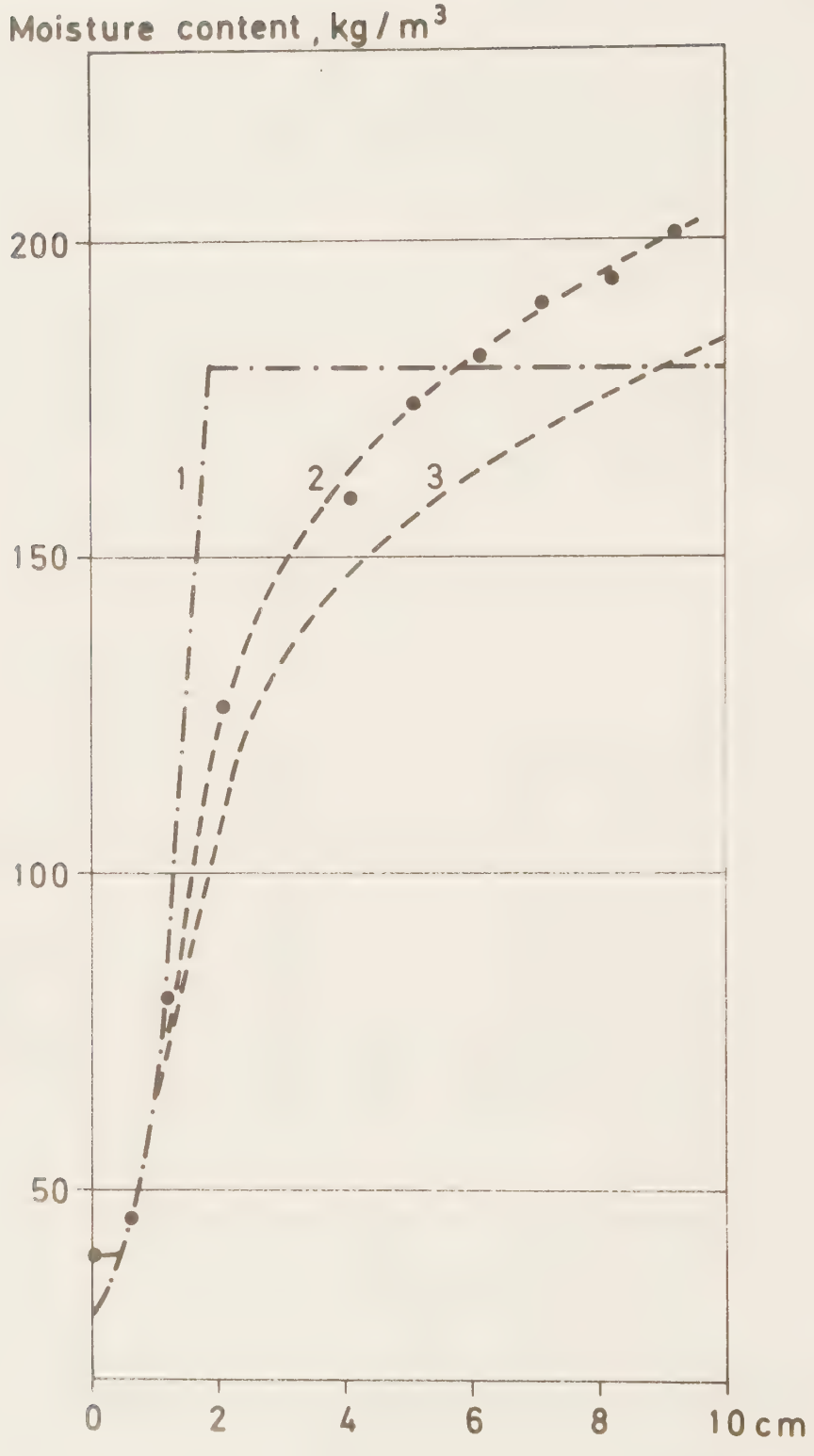


Fig. 38. Moisture distribution in the Ytong roof according to measurements of Vos (1967) and the following calculations:
1. according to Vos (1967)
2. SRS-model, capillary sat. at 335 kg/m^3
. SRS-model, capillary sat. at 295 kg/m^3.

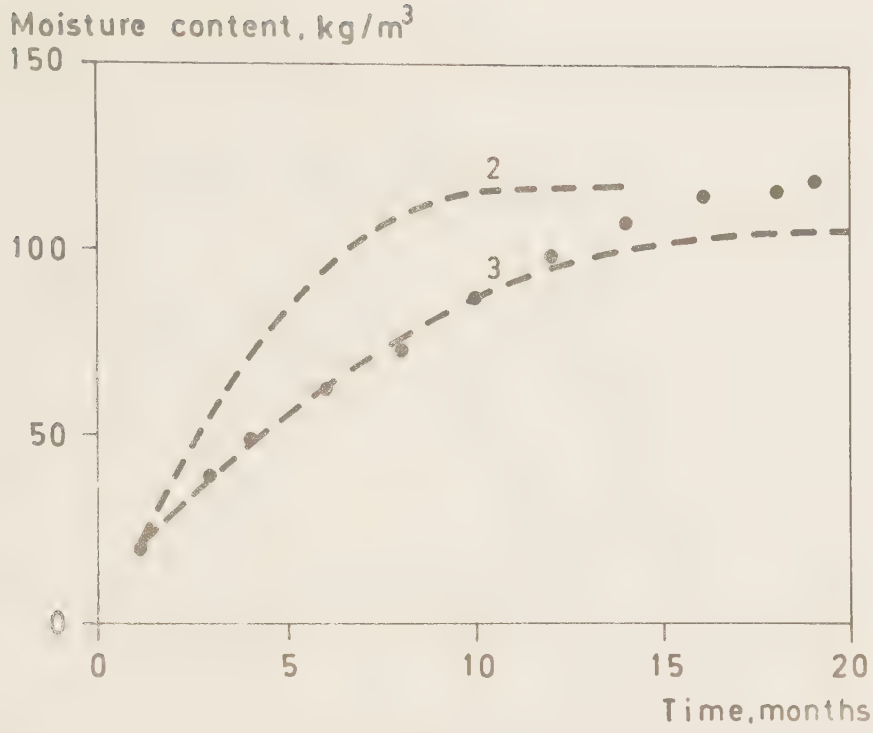


Fig. 39. Mean moisture content as a function of condensation time. Measured by Vos (1967), and calculated with the SRS-model for two cases, designated:
2. w_s = 300 kg/m^3 and D_T constant in the hygroscopic range
3. w_c = 335 kg/m^3 and D_T variable as described in Chapter 3.2.

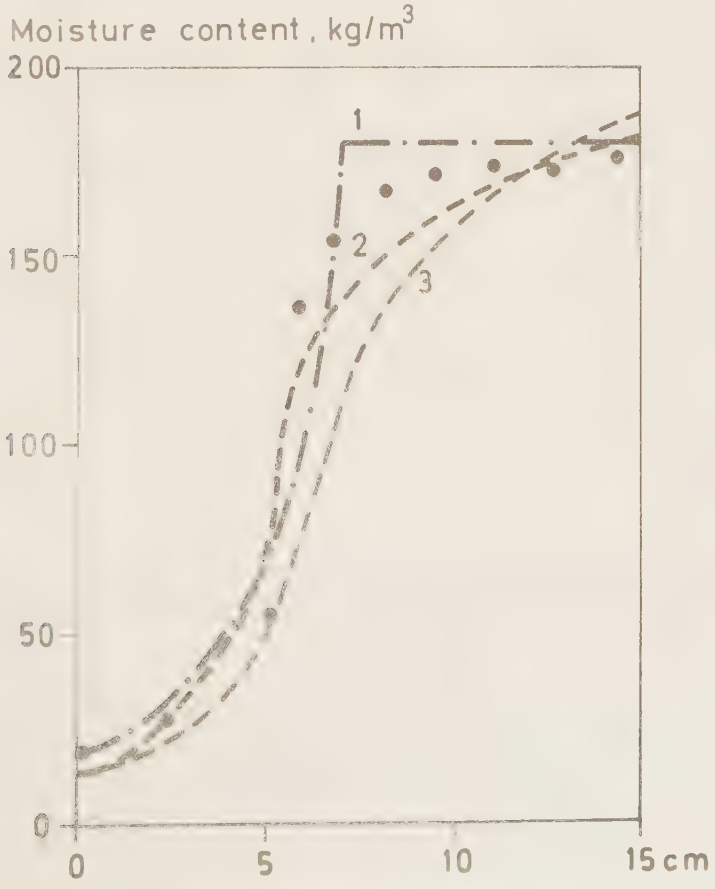


Fig. 40. Moisture content distribution after 20 months. Calculations: 1. according to Vos (1967) 2. and 3. as in Fig. 39.

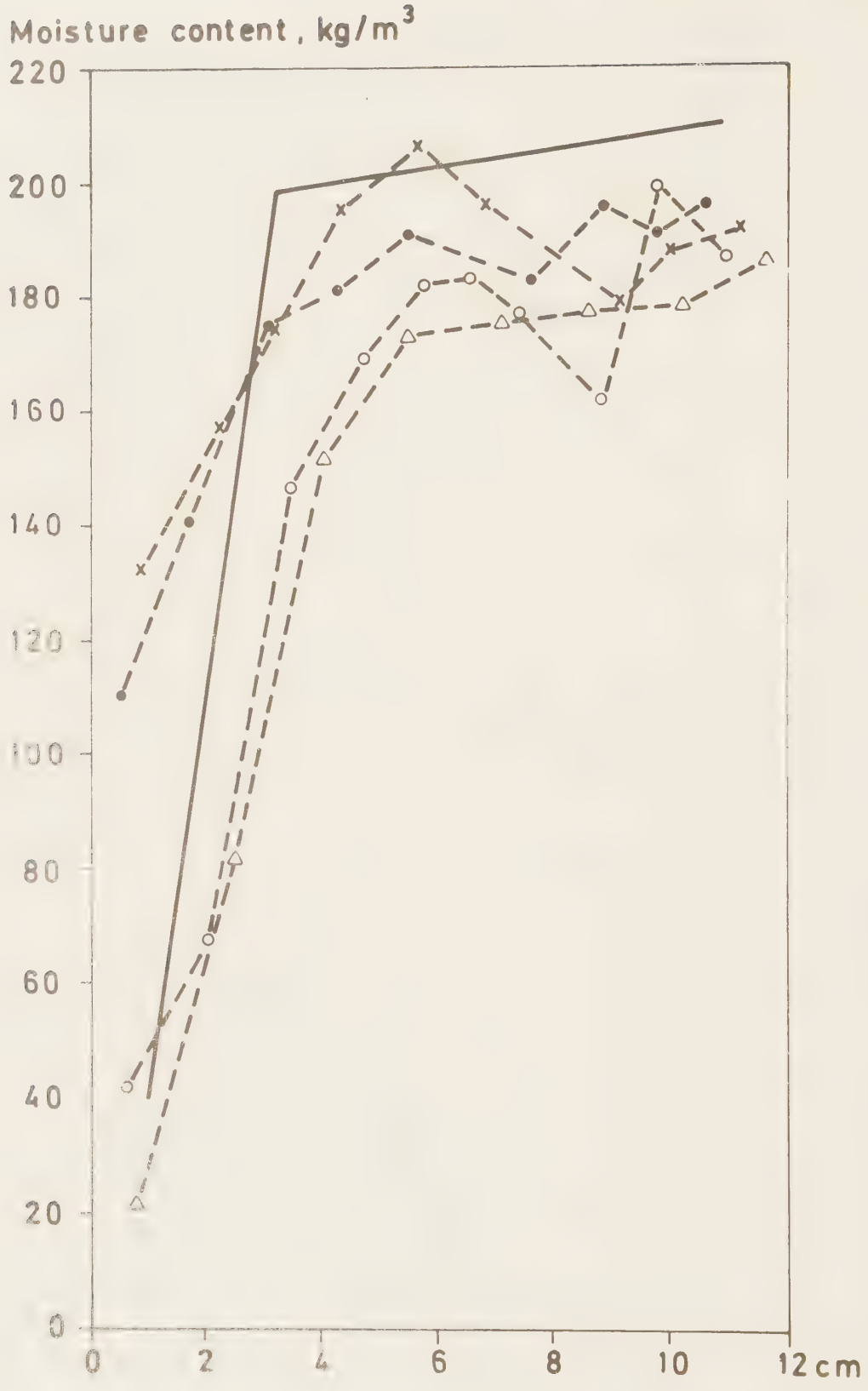


Fig. 41. Moisture content distribution in the aerated concrete slab (sort S) after 3-4 months of exposure to a temperature gradient 335 K/m (test of Hanson, 1957).
● x = close to the sides of the slab
△ o central area of the tested slab
—— calculated
measured.

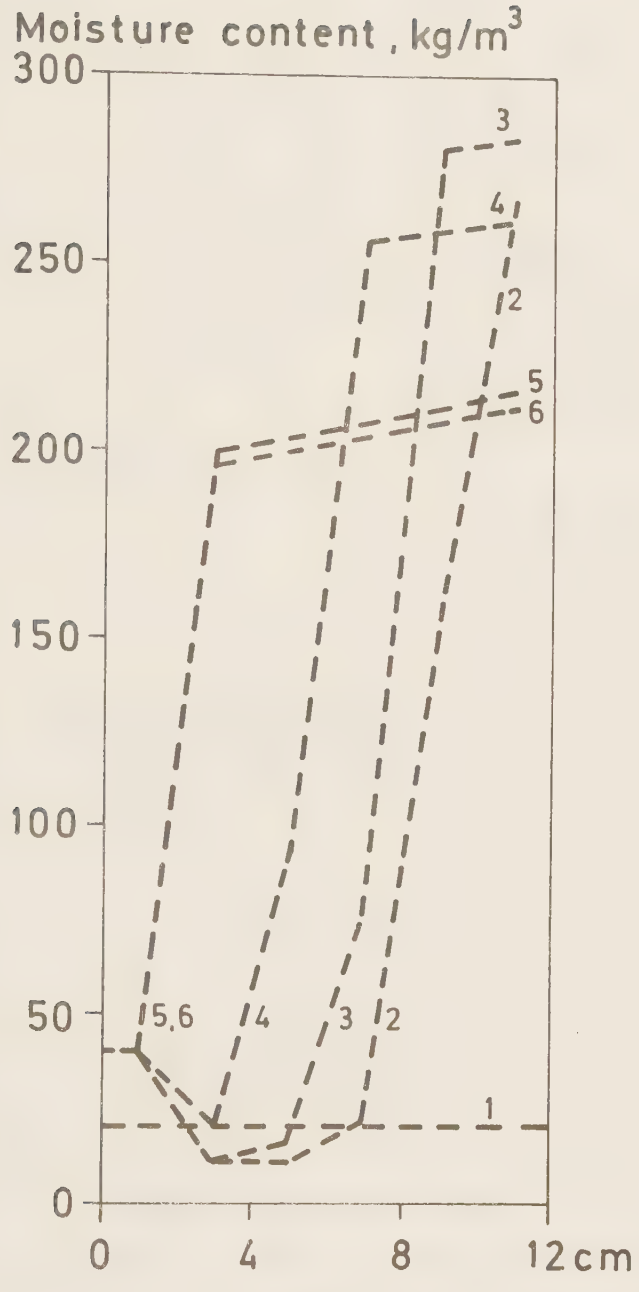


Fig. 42. Moisture content distribution calculated for the test conditions of Hanson (1957)
1. at the start
2. after 20 days
3. after 50 days
4. after 100 days
5. after 150 days
6. after 300 days.

vapour permeability coefficient. Two of his measurements are discussed below. They were called test (1): ϕ_1 and test (1): ϕ_4. For the respective tests he reported the following:

Test contitions:	(1): ϕ_1	(1): ϕ_4
permeability in g/day mm Hg	1.11	20.69
temperatures of air	23.8/-5.5°C	21.9/-5.8°C
temperatures of surfaces	21.2/-0.5°C	15.7/0.1°C
relative humidities	0.39/0.70	0.70/0.70
temperature gradient	434 K/m	318 K/m
tested area 0.48×0.231 m^2		

The following data are calculated from his measurements:

difference in partial pressure	6.58 mm Hg;	11.8 mm Hg
moisture flux in kg/m^2 s	3.7×10^{-7}	12.2×10^{-6}

Moisture contents calculated for the above described boundary conditions are 40 and 55 kg/m^3 respectively in the ϕ_1-test and 55 and 55 kg/m^3 in the ϕ_4-test.

Fig. 43 and Fig. 44 show moisture content distributions calculated with the SRS-model for the material properties as determined by Kooi (1971). These distributions show the interrelation between moisture flows caused by the capillary suction and temperature gradients.

In both cases thermally driven flows are decisive for the total movement of moisture. In the ϕ_4-test a temperature gradient is the only driving force of the moisture movement, in the ϕ_1-test a moisture content gradient causes an opposite flow, thus decreasing density rate of the total transfer.

Fig. 43 and Fig. 44 show conditions of tests and calculated moisture content distributions. Calculations were performed for two different and constant levels of thermal moisture diffusivity coefficient and a curve approximated as follows:

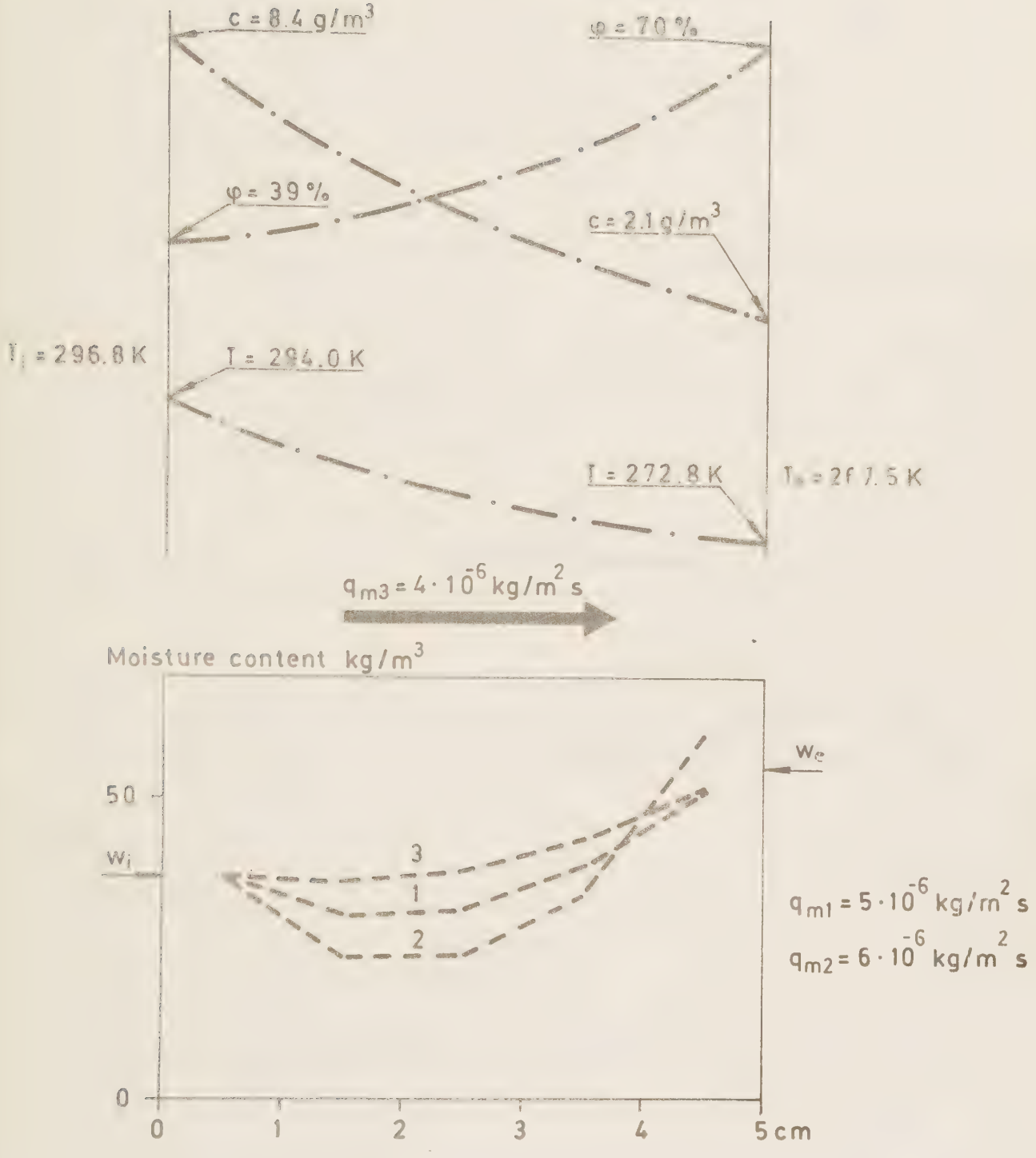


Fig. 43. Moisture content distribution and conditions of the ϕ_1-test (1) of Lund-Hansen (1967). Thermal diffusivity assumed as follows:
1. constant, calculated from dry-cup method
2. constant, two times larger than above
3. level as above, but variable as described in Chapter 3.2.

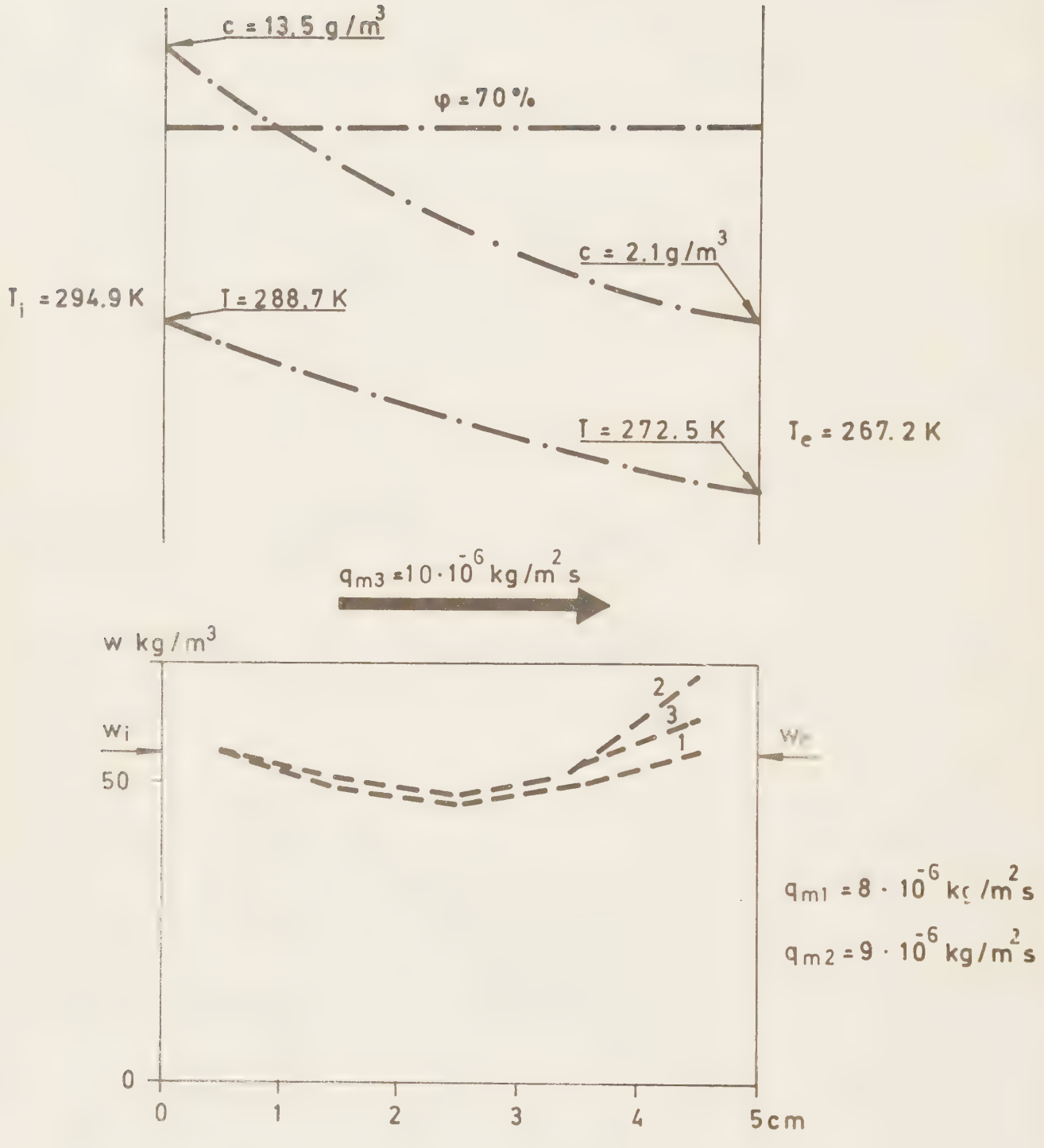


Fig. 44. Moisture content distributions and conditions of the ϕ_4-test (1) of Lund-Hansen (1967). Thermal diffusivity assumed as follows:
1. constant, calculated from dry-cup method
2. constant, two times larger than above
3. level as above, but variable as described in Chapter 3.2.

(i) D_T increases about four times between the limit of calculations and equilibrium moisture content at about 98 % RH.

(ii) A constant level continues up to the capillary saturation.

(iii) D_T decreases from the constant level if the moisture content is higher than the capillary saturation reaching zero value at absolute saturation.

It may be seen in Fig. 43 and Fig. 44 that thermally driven flow is the most important part of the total moisture transfer under the above conditions. In the ϕ_4-test, where the moisture content would be the same over the whole structure in absence of the temperature gradient, the total flux was calculated to be about 10×10^{-6} kg/m^2 s, which may be compared to 12×10^{-6} kg/m^2 s in the test.

In the ϕ_1-test where the thermally driven flow counteracts the isothermal transfer, total flux is diminished to about 4×10^{-6} kg/m^2 s according to the above calculations, while tested values is about 10 times less.

Ahlgren & Adamson (1972) calculated $g_m = 3.4\times10^{-7}$ kg/m^2 s for the ϕ_1-test of Lund-Hansen using, however, experimentally determined value of D_T about 8 times smaller than D_T used here and based on material properties of Kooi (1971).

Different measurements of thermal moisture diffusivity performed for aerated concrete are relatively scattered (see: Ahlgren & Adamson, 1972; Vos & Tammes, 1969; Kooi, 1971; Nicolajsen, 1973). Extreme figures out of the summary done by Nicolajsen (1973) are as follows: $D_T = 1\times10^{-11}$ kg/m s K for $T \cong 283$ K, $\phi \cong 90$ % RH used by Vos a Tammes (1969), and $D_T = 1\times10^{-8}$ kg/m s K for T = 293 K and moisture content $\omega \cong 50$ kg/m^3 used by Kooi (1971) or $D_T = 1.4\times10^{-8}$ kg/m s K for $T = 308$ K and $\phi = 75$ % RH used by Nicolajsen (1973).

Comparing with the vapour permeability measurements for aerated concrete 500 Kp/m^3 determined at Inst. für Bauphysik, Holzkirchen $3.0\text{-}5.2\times10^{-11}$ kg/m s Pa, at Inst. for Building Research, Trondheim, $3.4\text{-}8.0\times10^{-11}$ kg/m s Pa, at Inst. for Building Technology, Lund, $3.8\text{-}5.5\times10^{-11}$ kg/m s Pa, one may notice how great are practical difficulties in a direct

testing of the D_T-coefficient.

For this reason we shall use Eq. (23) which recalculates vapour permeability into the thermal moisture diffusivity as only way of determination of the D_T. Nicolajsen measured for T = 308 K the following values of D_T

$$4 \times 10^{-9} \text{ kg/m s K, for } \phi = 40 \text{ \% RH}$$
$$7.5 \times 10^{-9} \text{ kg/m s K, for } \phi = 60 \text{ \% RH}$$
$$14 \times 10^{-9} \text{ kg/m s K, for } \phi = 75 \text{ \% RH}$$

and vapour permeability coefficient at $\phi \simeq 75$ % RH for the same material $\delta' = 6 \times 10^{-11}$ kg/m s Pa i.e. $\delta = 8 \times 10^{-6}$ m^2/s. From Eq. (23) may be obtained $D_T = 16 \times 10^{-9}$ kg/m s K which gives sufficient agreement with the test.

6.5 Drying of porous materials.

A density of moisture flow from the dried specimen, called the drying rate, is usually used to describe a drying process.

The drying rate depends on environmental conditions, for instance: the surface mass-transfer coefficient and a relative humidity of the ambient air, as well as moisture transport inside the material. The following factors determine the drying rate:

(i) Environmental parameters:

1. air velocity, roughness of the surface
2. temperature difference between the ambient air and the material surface,
3. vapour concentration in the ambient air,
4. ambient air temperature

(ii) Parameters for internal moisture transfer:

1. moisture content and moisutre content gradient in the layer adjacent to the dried surface,
2. temperature gradient in the layer adjacent to the dried surface,
3. geometry of the dried material,
4. initial moisture content,
5. energy status of the air ev. entrapped in the liquid water.

For a given set of conditions, as listed above, two criteria are determined:

(i) Maximum possible moisture outflow from the geometrical surface plane to the ambient air.

(ii) Maximum possible moisture movement from the body of the material to the geometrical surface plane.

The geometrical surface plane is assumed to be a boundary between outer and inner transfers.

The outer and inner moisture fluxes must be equal owing to continuity conditions. As a result of this requirement a certain moisture content distribution in the material layer adjacent to the goemetrical surface plane is created, so that the inner and outer moisture fluxes are equal. The maximum of the smaller flux determines the drying rate.

If the smaller flux is the outer flux, the first range of drying is obtained. The drying rate is either constant or slightly decreased and the first knick point of drying rate ends the range of drying where the material properties plays less significant role than the outer conditions.

Krischer (1956, 1963) assumes that the evaporation of water in the first range of drying, occurs only at the material surface. Lykov (1956) [1/] disagrees with this viewpoint and assumes that evaporation takes place inside the pores already in the first drying range.

In this report, the first range of drying is associated with the outer conditions determining the drying rate. The inner transport decreases in direct proportion to the moisture content and at a certain moment it is smaller than the outer transport. At this moment the second range of drying begins. The mass-transfer coefficient at the surface is no longer significant for the drying rate.

In the second drying range the moisture transport to the geometrical surface plane (the inner transport) consists of two parts:

(i) A combined liquid-vapour transport to the place where water evaporates.

(ii) A process of diffusion through an unmovable air layer of a variable thickness, which leads vapour out of the specimen.

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1) Cf. remarks by Ginzburg in the Russian language translation of Krischers book, Moscow, 1961.

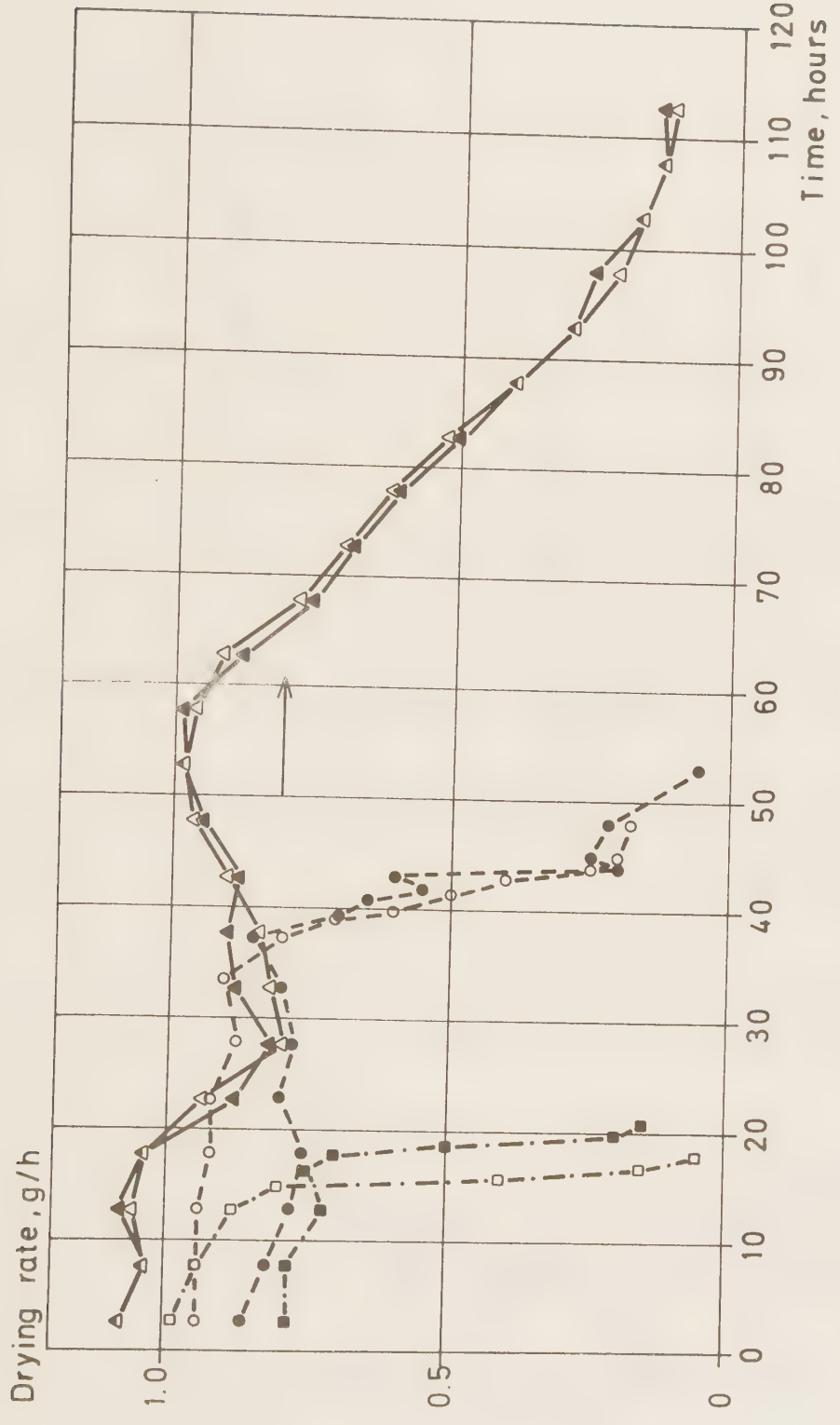

Fig. 45. Drying rate of the standard gypsum (w_s = 440 kg/m^3, ρ = 1250 kg/m^3) as function of time. From the research of Ahlgren (1973). Thickness of the specimens Δ 51 mm, ▲ 49 mm, o 22 mm, ● 23 mm, □ 9.5 mm, ■ 9.5 mm.

The liquid part of the moisture flow decreases in direct proportion to the moisture content and at a certain point it becomes insignificantly small. This point is known as the second knick point of drying. It may also happen that this knick point is not visible in the drying run.

Whether these knick points, or at least the first knick point of drying can be readily determined was investigated by Ahlgren at the Building Materials Section of the Lund Institute of Technology. His research is not yet published but with his kind permission some of these tests are reported below.

Ahlgren performed drying experiments in a climatic chamber with the following conditions: T = 293 K, ϕ = 43 % RH, and constant air velocity.

By means of an authomatic balance a unidimensional drying from full saturation (obtained in a vacuum tank) was tested. Thickness of the specimens varied between 5 and 25 mm.

Fig. 45 shows drying of a few specimens with different thickness. Drying rate of the standard gypsum is shown as a function of time.

Fig. 46 shows drying rate as a function of the mean moisture content for aerated concrete with density about 500 kg/m^3 and Fig. 47 shows the same for a clay-brick.

It may be seen in the above figures that small and large specimens produce slightly different drying rates. This is particularly notable in the first range of drying.

Some care needs to be taken in setting up these experiments. Inhomogenity and influence of the entrapped air do not allow testing too small specimens. If testing too thick a specimen, the mean moisture content may deviate from the level in the layer adjacent to the drying surface.

It seems that 10-15 mm distance of the moisture transfer i.e. 20-30 mm thick specimens would satisfy the above requirements.

Fig. 48 and Fig. 49 show the drying rate as a function of moisture content for sand-lime and clay-brick respectively.

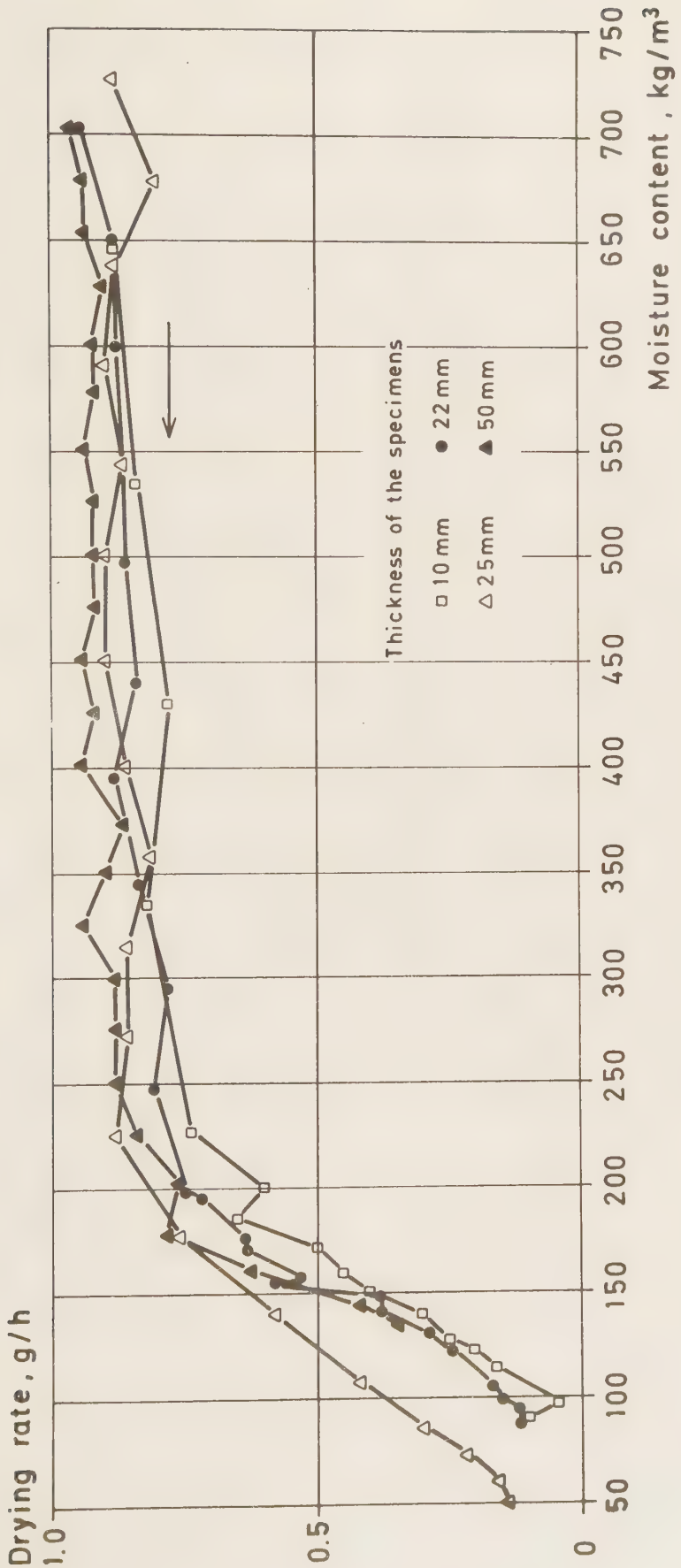

Fig. 46. Drying rate of the aerated concrete (ρ = 500 kg/m^3) specimens with different thickness. From the research of Ahlgren (1973).

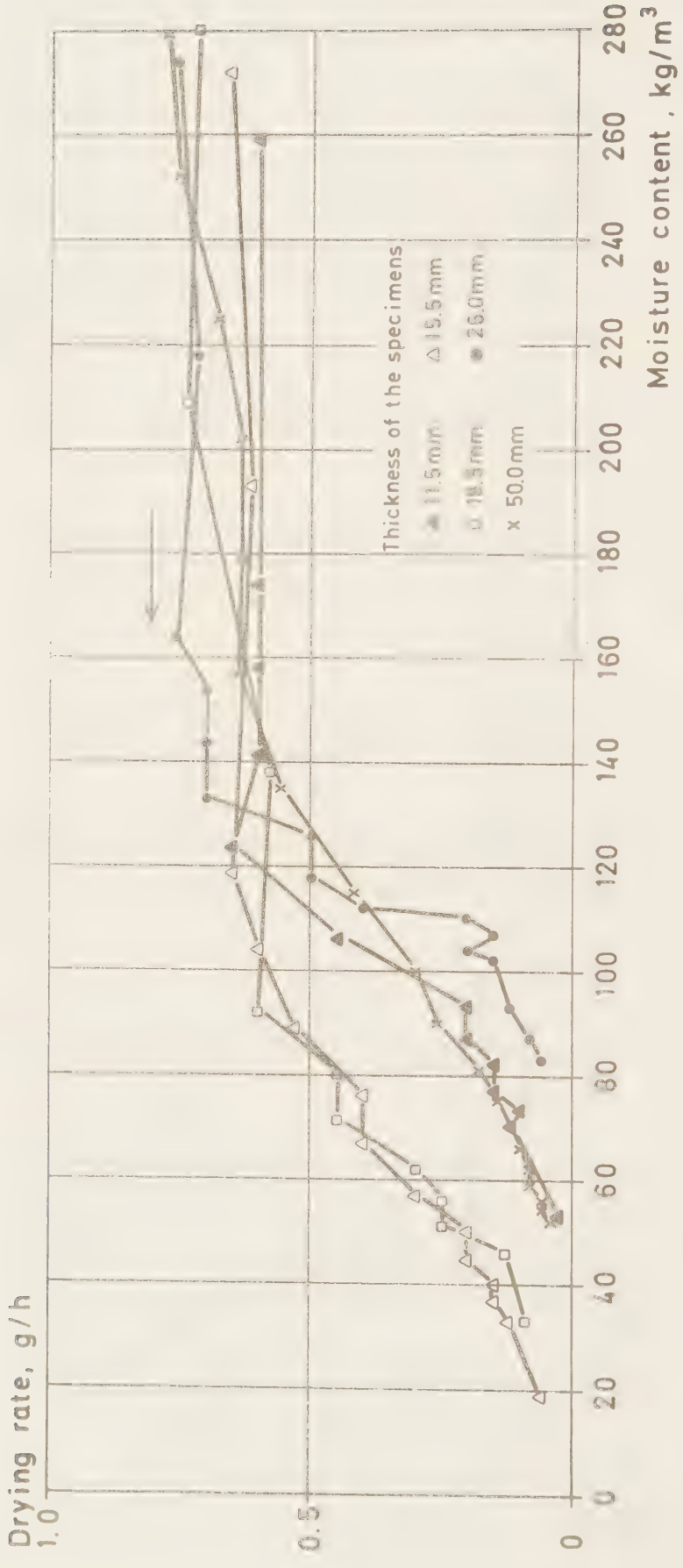

Fig. 47. Drying rate of the clay-bricks (ρ = 1800 kg/m^3, $w_{..}$ = 300 kg/m^3). Specimens with different thickness. From the research of Ahlgren (1973).

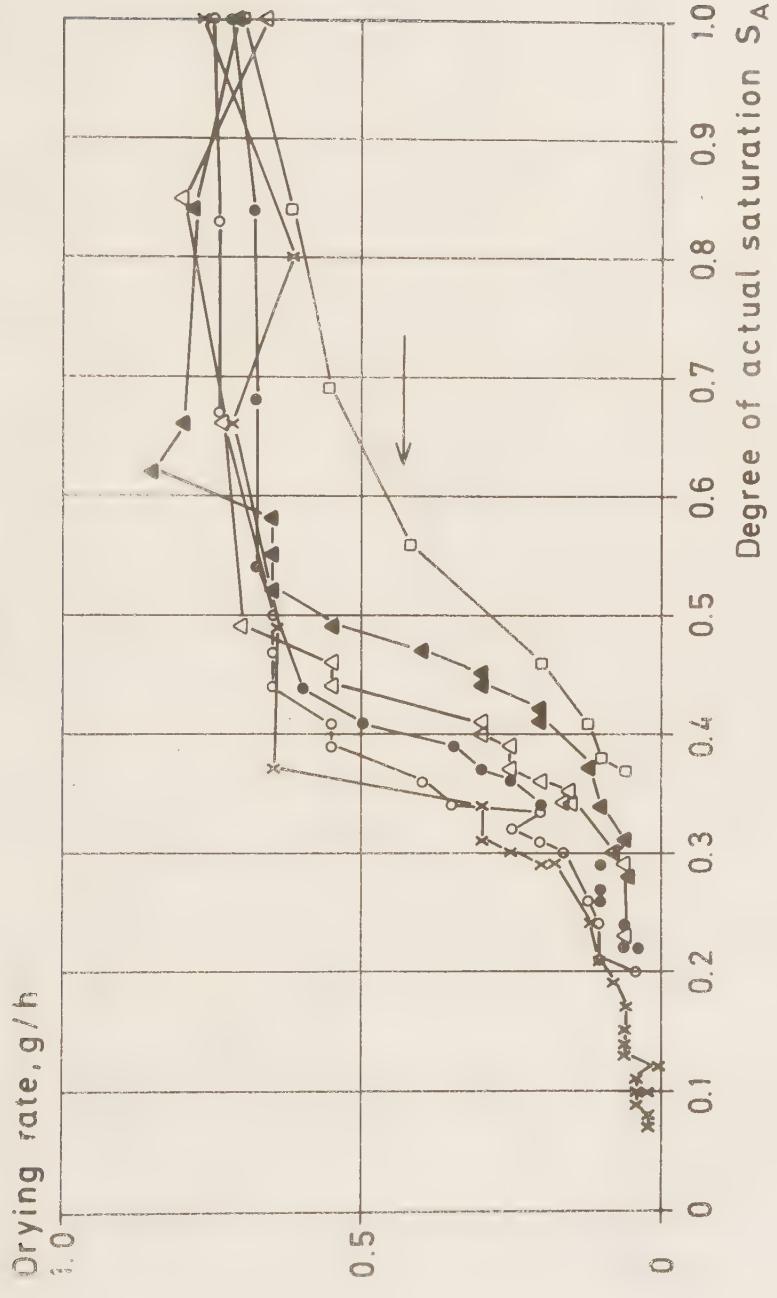

Fig. 48. Drying rate of sand-lime bricks. Six specimens intended to be identical. Thickness about 25 mm. From the research of Ahlgren (1973).

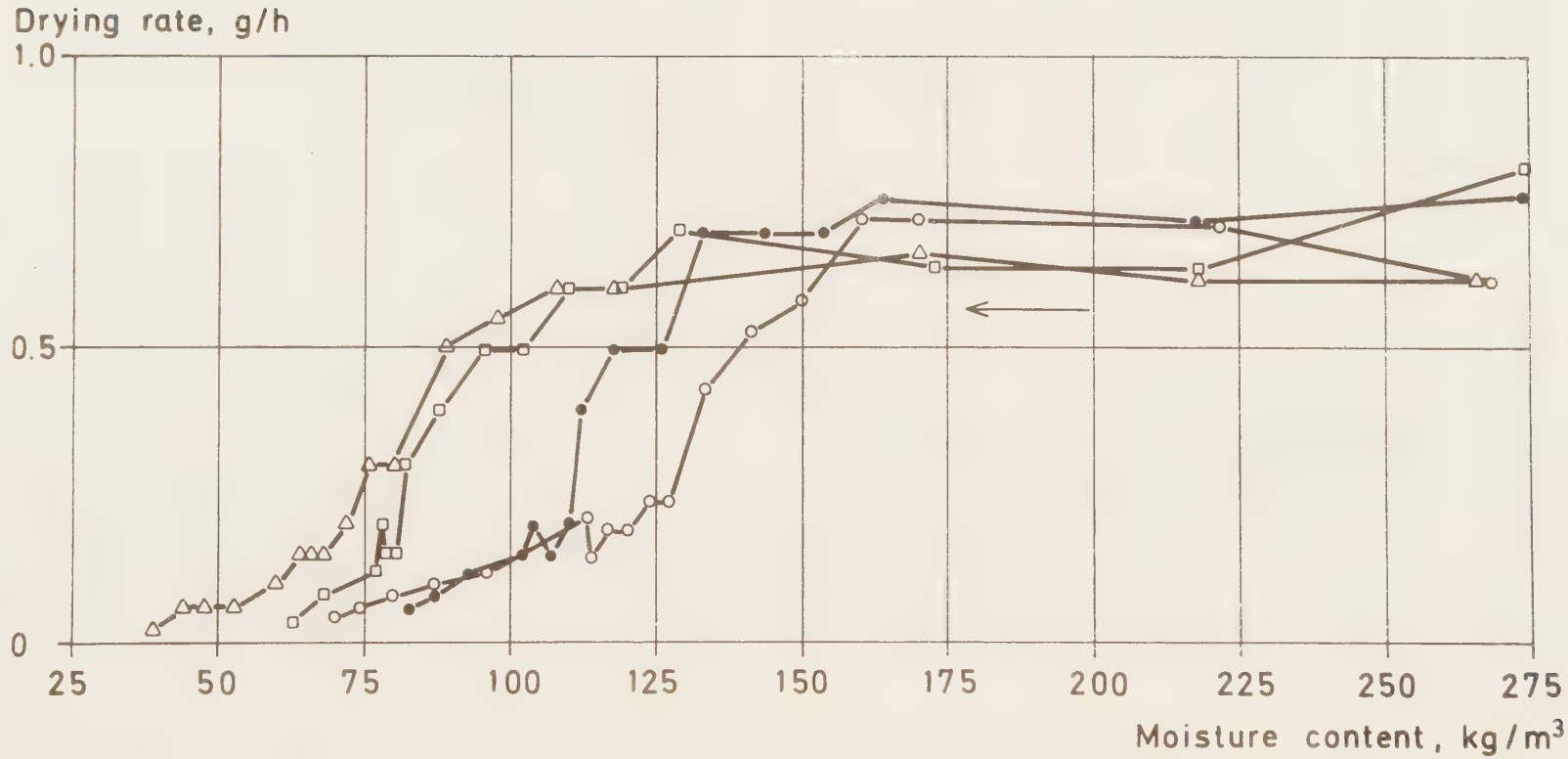

Fig. 49. Drying rate of the clay-brick specimens. Four specimens from the same lot. Thickness about 25 mm. From the research of Ahlgren (1973).

Looking at the above figures it may be concluded that they do not produce any clear approximation of the knick points. A simple drying test may only indicate an approximate range where the first drying range turns into the second one.

Of course, carrying out the drying tests under different drying conditions one can obtain a better impression (Vos, 1967) but even such a test is influenced by a number of factors.

One of the most significant factors is the initial moisture content.

Fig. 50 shows results of Ahlgren relating to standard gypsum where two runs were started at the absolute saturation and one at much lower level of the moisture content.

Initial moisture content was also investigated by the author. Three series of the clay-bricks (product K) of equal dimensions were immersed in water after some preparation. All the specimens had been wetted and dried few times and had different moisture contents and moisture content distributions. They were immersed in water for 1 hour and dried immediately afterwards. Weight changes were noted with accuracy of 5 sec and 5/10000 grams.

Fig. 51 shows the drying rate of these equally sized specimens, dried under constant conditions ($T = 295$ K and $\phi = 50$ % RH).

It appears that both the moisture content level at the beginning and the hysteretic background have an influence on the drying rate.

Fig. 52 shows drying of the same specimens but started from the full saturation. The drying rate shows a sharp decrease in the very first moment of drying and an increase later on, but still during the first drying stage. It contradicts the assumption that during the whole first drying stage the evaporation must take place at the material surface.

One may conclude the above reviewed drying experiments, noting that the concept of a knick point in the drying rate is rather vague. It may of course be experimentally obtained as a defined change of curvature but is not reproducible for another set of drying conditions. For instance,

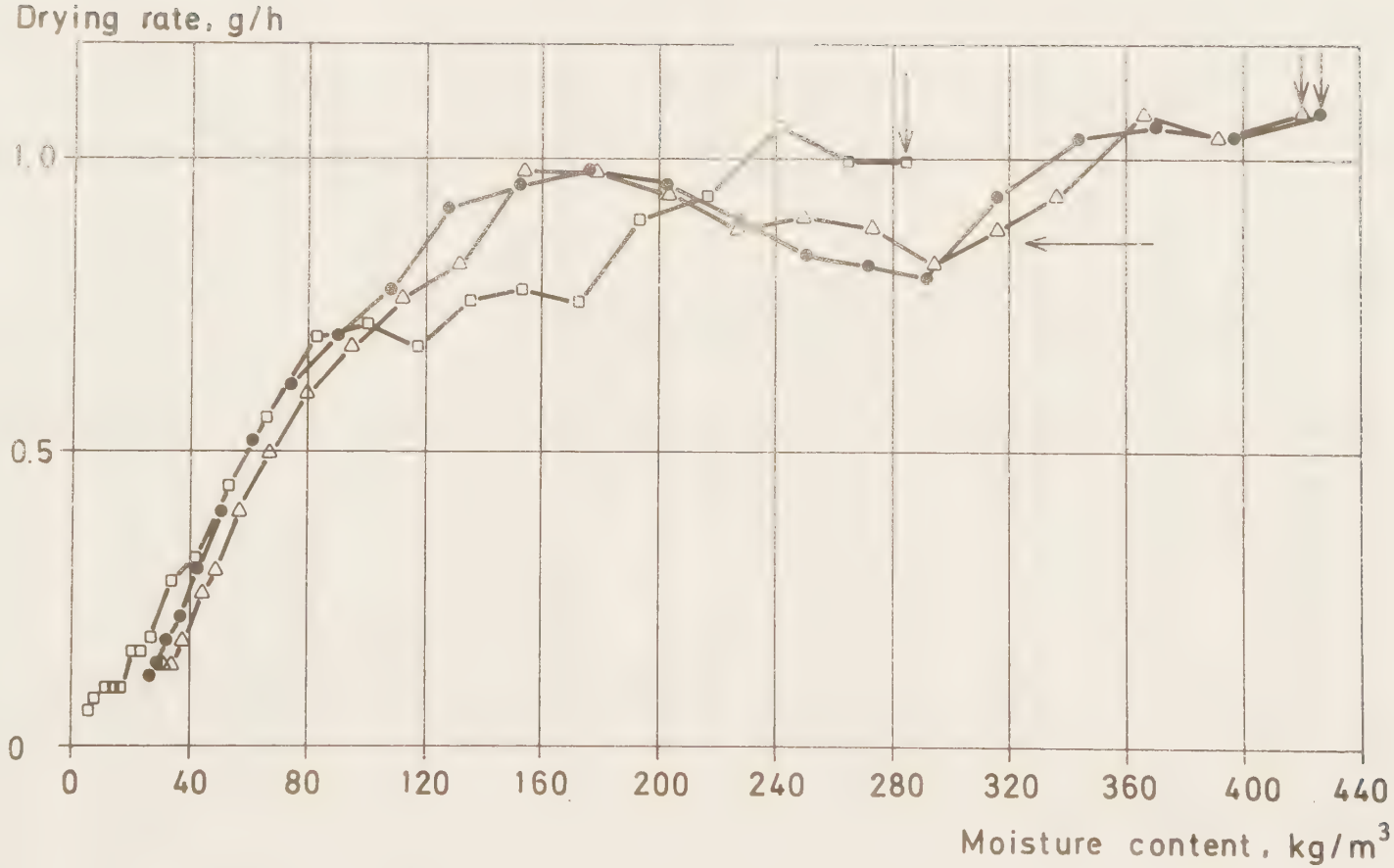

Fig. 50. Drying rate of the standard gypsum as influenced by the starting moisture content. From the research of Ahlgren (1973).

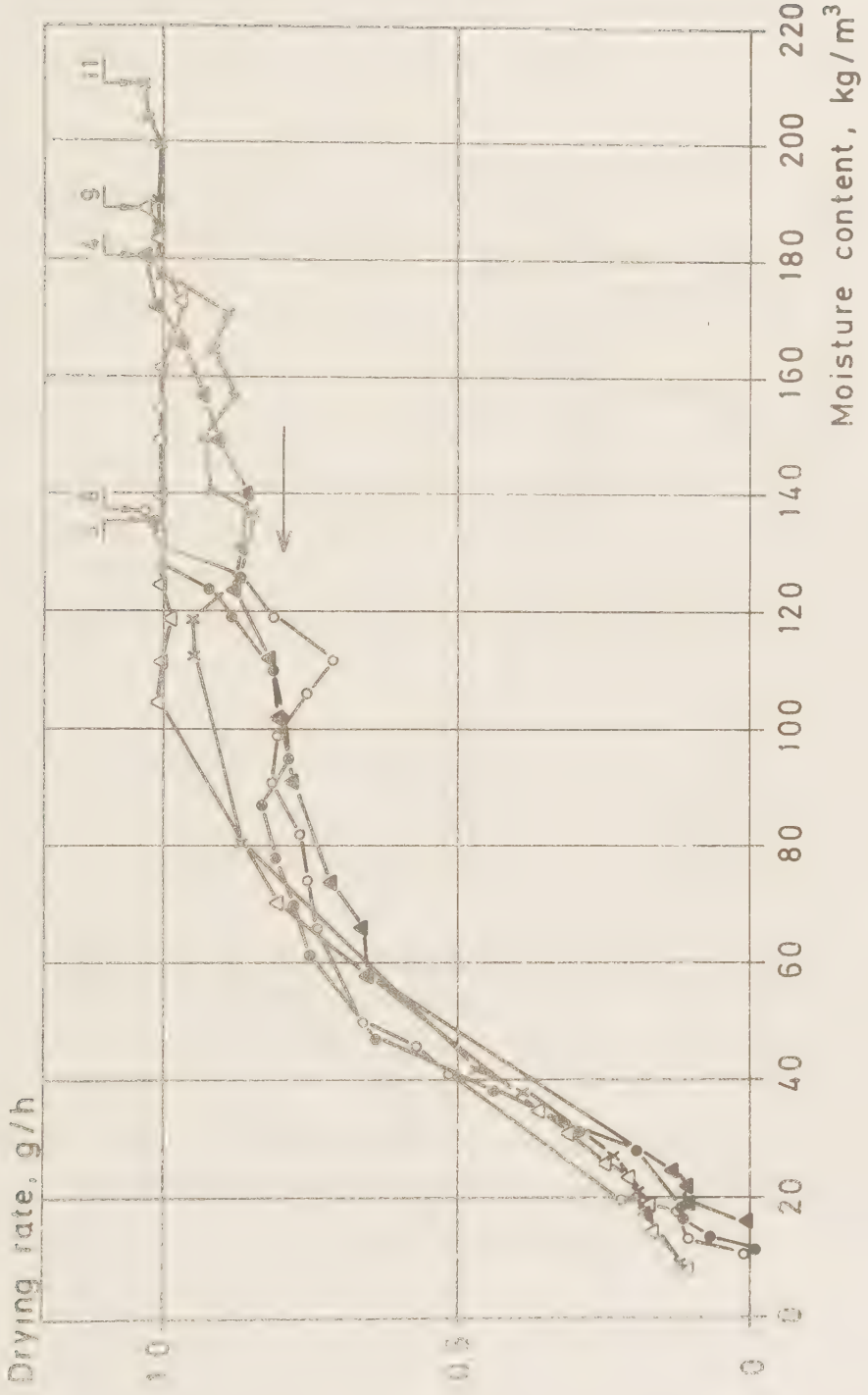

Fig. 51. Drying rate of the clay-bricks as influenced by the starting moisture content.

Fig. 53 represents the extreme case of drying when the drying rate is not decreased during the whole first stage and is equal to the maximum

Such a drying is possible only when:

1. the gradient of moisture content is practically zero in the whole specimen as long as moisture content exceeds the first knick point of drying.

2. diffusivity coefficient does not decrease in this range of the moisture content, except in the first stage (see water transition zone in Bomberg, 1971).

The real drying rates deviate slightly from the above scheme because of the coupling between external and internal transports.

At the very first moment of drying the gradient of moisture content practically does not exist. When it develops, the moisture content at the material surface decreases and evaporation i.e. external transfer decreases also.

At this stage the character of the drying rate becomes affected by the thickness of the specimens. For thicker specimens larger difference in the moisture contents must be developed. (See: Fig. 45.)

Moisture content in the material layer adjacent to the dried surface becomes much lower than a mean moisture content for the whole specimen. As the moisture transfer to the material surface depends on the diffusivity coefficient in this layer, the flux of moisture moved to the surface and later removed from the specimen may be altered. The drying rate related to a mean moisture content of the specimen may deviate from straight line in the first drying stage, as shown in Fig. 54.

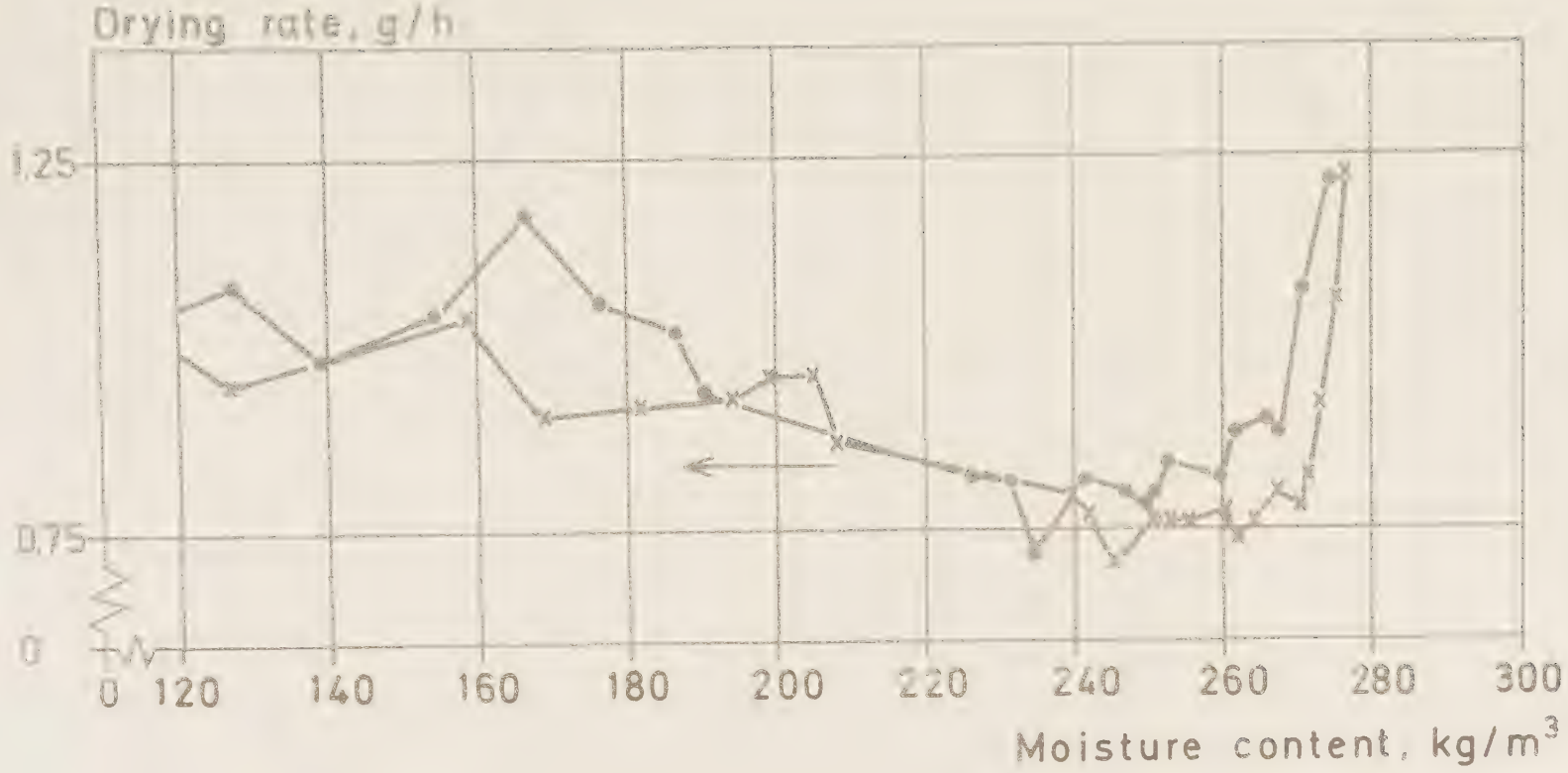

Fig. 52. Drying rate of the clay-bricks as influenced by the starting moisture content equal to the absolute saturation.

one may look at Fig. 51 and compare specimens number 4 and 9 (the same material, the same conditions of drying, geometry, even starting moisture content). One would obtain the knick point at 58 kg/m^3 and 105 kg/m^3 respectively.

Secondly one may conclude that the drying rate in the first stage of drying may have quite different character. It may be almost constant (as specimen 9 in Fig. 51) or almost lineary decreasing (specimen 4 in Fig. 51) but even increasing after a first decreasing period (specimens 5, 8, 11).

These anomalies are discussed in Fig. 53 and Fig. 54.

Fig. 53 shows two variables:

$q_{e,max}$ = maximum possible flux from the geometrical surface plane, i.e. external flux which is constant for steady drying conditions

$q_{i,max}$ = maximum possible internal flux of moisture which is a function of moisture content

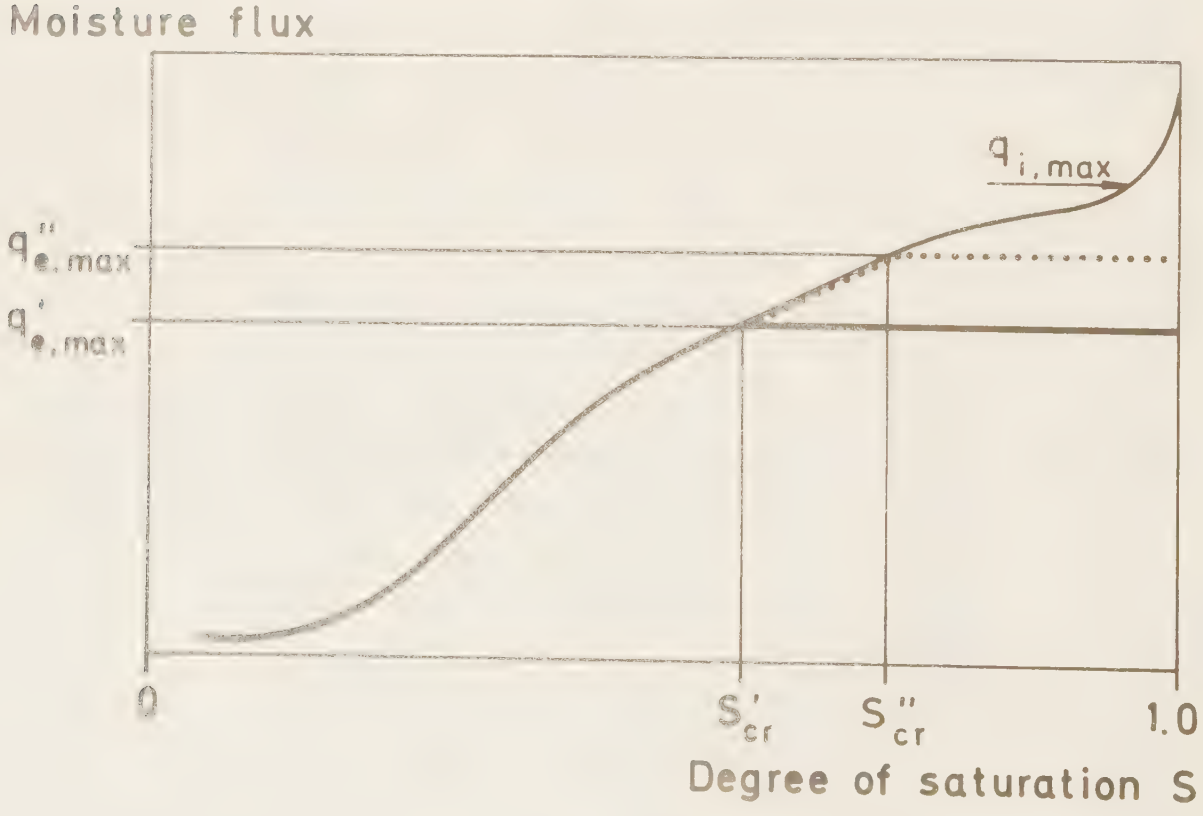

Fig. 53. An extreme case of the real drying rate. Two different drying processes are shown exemplifing various surface coefficients of mass transfer.

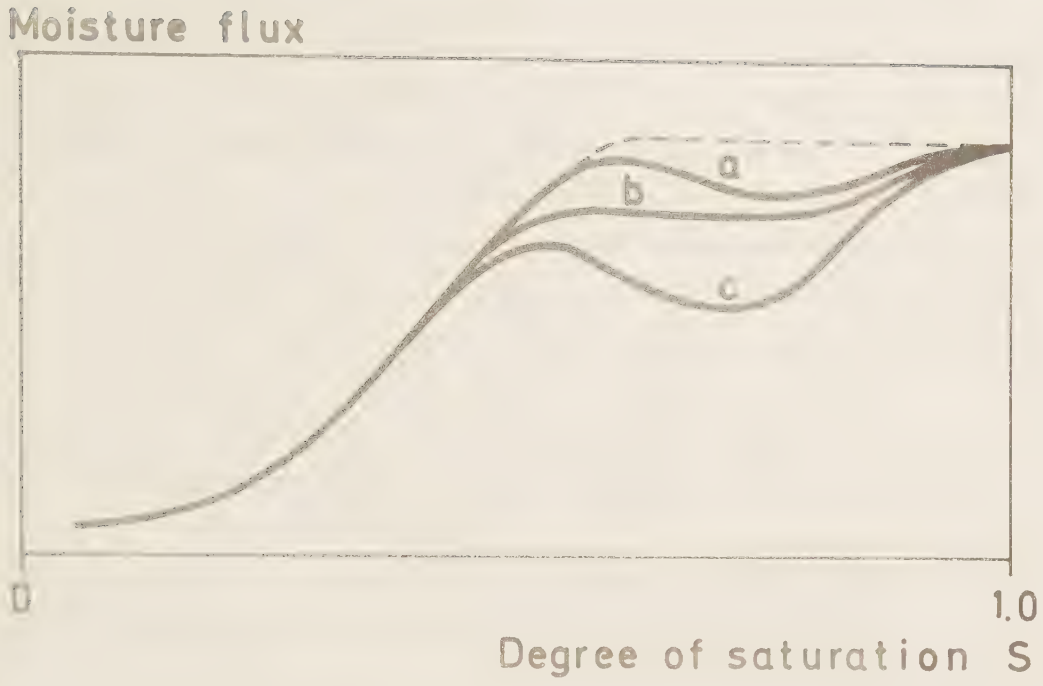

Fig. 54. More probable cases of the real drying rate.

Curves (a), (b), (c) in Fig. 54 represent different cases of drying. Case (a) and (c) are most probable for rather high external flux and not too thick specimens. Case (c) seems to apply to somewhat thicker specimens. Case (b) is most likely when evaporation is low, comparing to maximum possible internal flux of moisture.

Some other factors may also influence the drying rate e.g. coating on the material surface. It changes the relation between suction and moisture content at the contact plane between the surface coating and the material, introducing a change in the driving force of the internal moisture flow.

The above discussion of drying processes referred to the experimental results. The primary function of this report is, however, to analyse opportunities for the calculations and therefore some computations will be compared with the measurements.

Some calculations of drying versus time were already shown in Fig. 34, while discussing an influence of different diffusivity curves on both the moisture content distribution and mean moisture content during drying.

Mean moisture content showed relatively good agreement, but the calculated and measured moisture distributions were different.

It was caused by an assumption that the surface mass-transfer coefficient was steady and independent of moisture content. Actually, it is dependent on moisture content in the first layer. As shown in Figs.45-52 the drying rate may decrease and increase while moisture content exceeds the hygroscopic range.

If calculated moisture flux to the environment exceeded the flux from the body of the material to the surface, the following errors may occur:

(i) the calculated moisture content is much lower in the first layer than the actual one,and the calculated gradient of moisture content exceeds the actual one,

(ii) the calculated resistance towards flow through the first layer was higher than the actual one, due to decrease in the moisture conductinty with falling moisture content

(iii) drying rate calculated in the following period of time may be less than in reality.as the second effect usually exceed the first.

Some authors discuss a lower rate of drying in the second period of drying if the drying rate was relatively high at the beginning. Such a conclusion, may, however, be more affected by errors of the calculational models than known experimental results.

If one would like to discuss drying rate, one must carefully write the boundary conditions in the model for the calculations.

As known, the evaporation rate from the material surface depends on the moisture content of the material. Different moisture contents are in conjunction together with different positions of the capillary menisca and the resistance in vapour diffusion from the menisca to the geometrical surface plane, is different.

Even assuming that the surface of coefficient mass-transfer at the material geometrical surface plane is steady, the transport between the first layer and the environment must be governed by the level of moisture content in the layer adjacent to the surface. In the SRS-model a moisture flux from

the surface of the material is determined as a function of both the moisture content of the material layer adjacent to the surface and the surface coefficient of mass transfer. The following ranges of moisture content are differently treated:

(i) moisture contents higher than the capillary saturation,

(ii) moisture contents between the capillary saturation and the first knick point of drying

(iii) moisture contents between the first knick point of drying and the critical moisture content

(iv) under the critical moisture content where moisture content of the material does not influence the moisture flux to the environment and only the surface coefficient of mass transfer plays role.

The influence of moisture content on the drying rate is introduced in the following way:

Above a first knick point of drying, the moisture flux is dependent on the diffusivity coefficient (determined by the actual moisture content in the first layer). Diffusivity coefficient at the capillary saturation is used as a standard reference level. When the diffusivity coefficient is higher than the reference level moisture flux may increase, however, not more than 100 %.

Between the first knick point of drying and the critical moisture content the moisture flux is assumed to be directly proportional to the actual moisture content.

In this way the assumed boundary conditions (and the drying rate which follows from them) are associated with the first knick point of drying. In turn, this concept is based on the drying velocity. The moisture content at the first knick-point of drying is placed between the critical moisture content and the capillary saturation as a function of drying velocity. It is assumed to be linearly dependent on drying velocity.

Drying in non-movable air with $\phi \cong 50$ % and T = 283 K produces a knick point at the critical moisture content, while drying process at the same conditions but T = 335 K produces the knick point at the capillary saturation.

The above discussed assumptions were introduced into a program. The program applied to the same test as already shown in Fig. 34. Results are shown in Fig. 55.

Calculations shown in Fig. 55 were carried out for the following conditions:

1. critical moisture content at 70 kg/m^3

2. critical moisture content at 80 kg/m^3

3. calculation as shown in Fig. 34.

Fig. 56 shows drying of the same material from absolute saturation. Measured values were determined by Jönsson (1973) by means of gamma-ray attenuation technique. Calculations were performed with both versions of the program.

The preliminary version gives better agreement in the mean moisture content determination, but nearly a complete disagreement in drying rate and distribution of moisture content (cf. Fig. 34).

The second version of the program gives perhaps worse agreement for the mean moisture content determination but allows for a judgement of the distribution of moisture content.

Fig. 57 shows the drying rate for the same material tested under different conditions, as follows:

(1) calculation carried out for the following conditions T = 295 K, $\phi \cong 50$ % RH, $\beta = 2 \times 10^{-3}$ m/s and already shown in Fig. 55

(2) calculation shown in Fig. 56, carried out for the same conditions except the starting moisture content, $\omega_o = 295$ kg/m^3 and also $\omega_o = 270$ kg/m^3

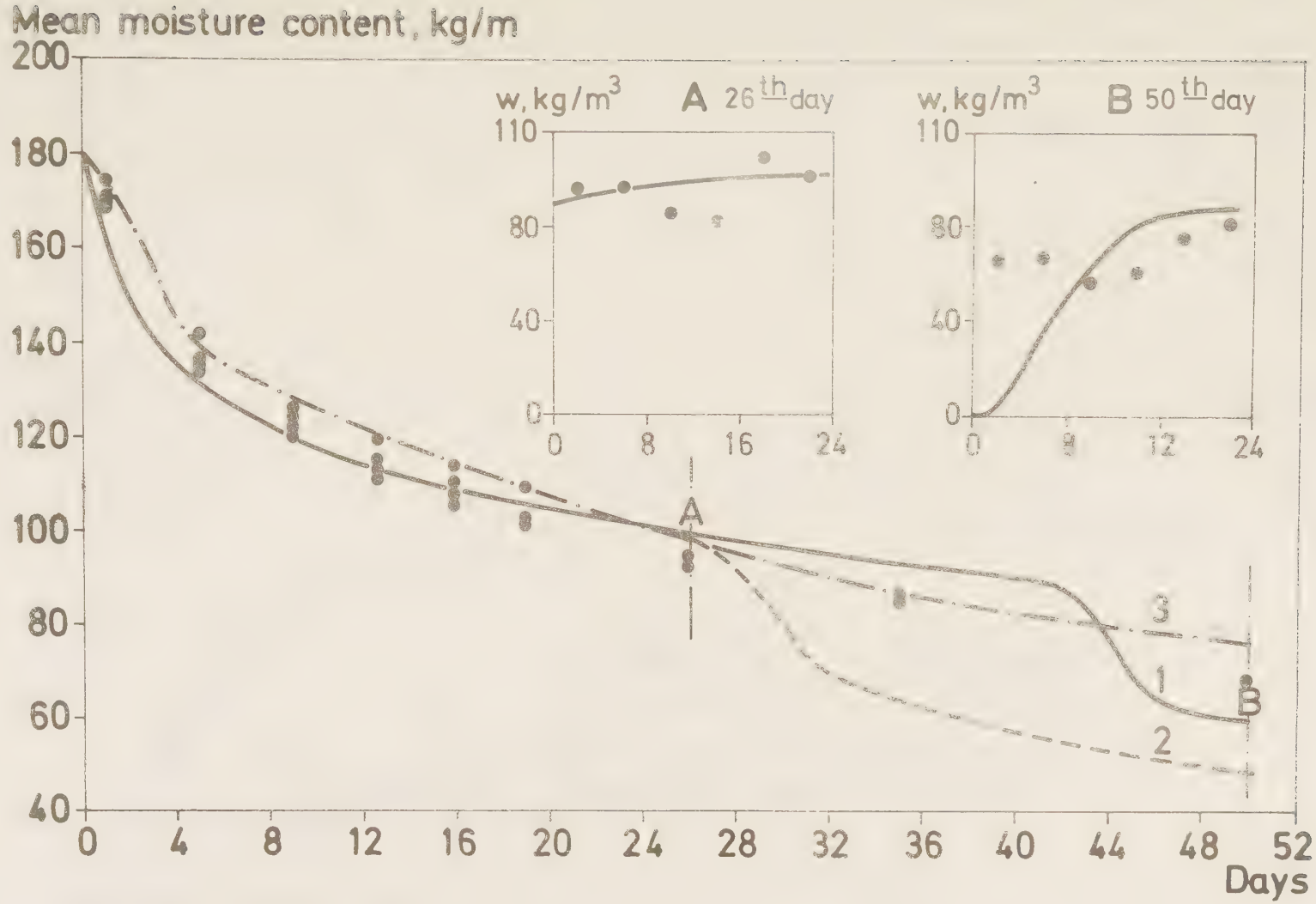

Fig. 55. One-side drying as shown in Fig. 34 calculated with the first program (curve 3) and with the second version of the program with the critical moisture content at 70 kg/m^3 (curve 1 and also moisture distributions) and 80 kg/m^3 (curve 2). Due to experimental facilities moisture distributions A and B were determined on two different specimens.

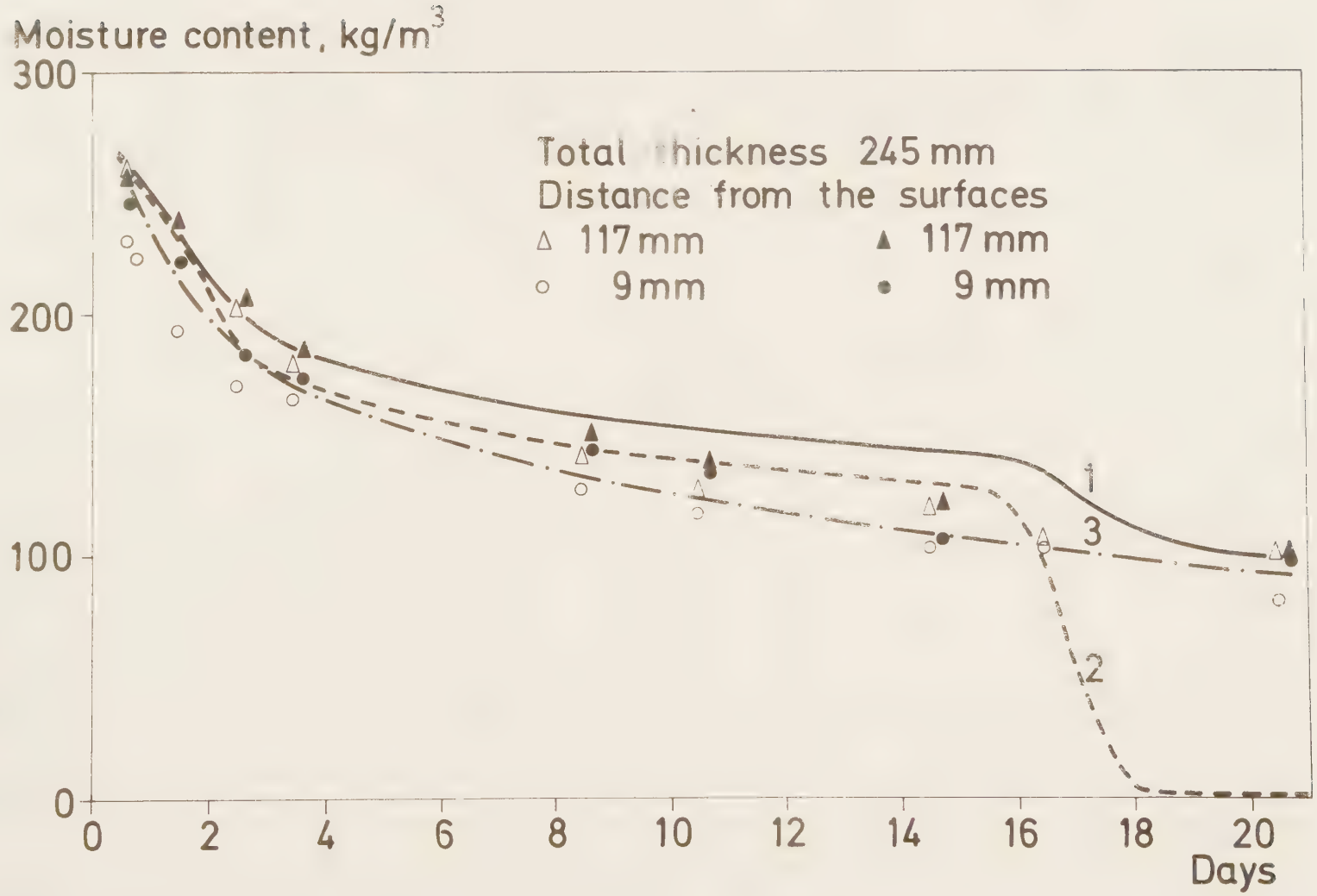

Fig. 56. Two-sides drying under steady conditions of the clay bricks. Measurements of Jönsson (1973) against calculations based on the diffusivity curve (c) from Fig. 32. 1. Mean moisture content acc. to the second program, 2. The first layer acc. to the second program, 3. Mean moisture content acc. to the first program.

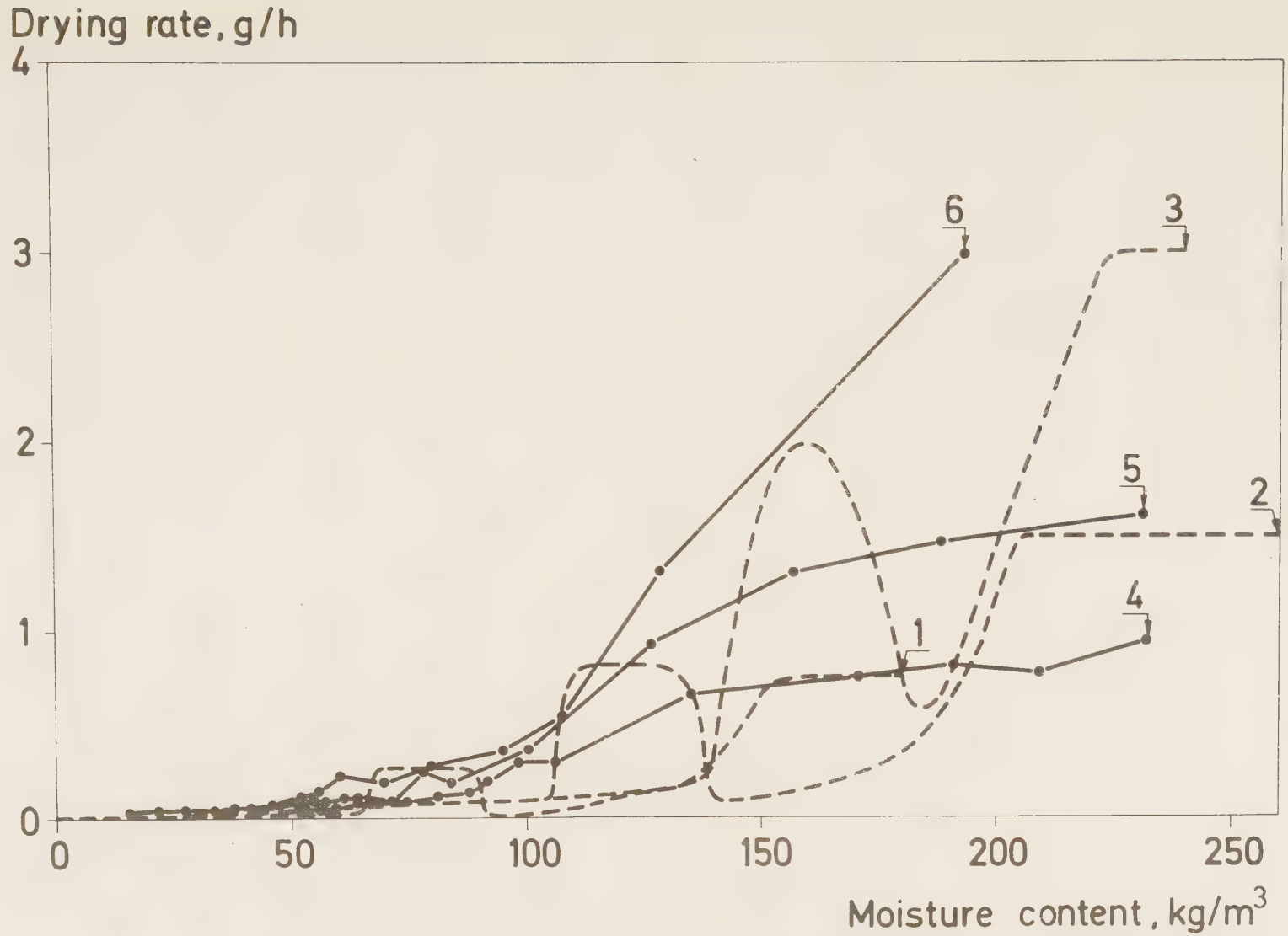

Fig. 57. Drying rate of the clay-bricks according to measurements and calculations. See text.

(3) calculation carried out for the following conditions: T = 295 K, $\phi \cong 50$ % RH, $\beta = 8 \times 10^{-3}$ m/s and $\omega_o = 240$ kg/m^3

(4) measured in the laboratory room, T = 295 K, $\phi = 50$ % RH. Wetted by means of free-water intake process to $\omega_o = 230$ kg/m^3.

(5) measured in the same conditions as (4) except that the water-intake process took place under vacuum. Air pressure was about 10 % of the atmospheric pressure.

(6) measured in the laboratory room as in (4) except that a ventilator produced a strong wind at the surfaces. Wetting to about 230 kg/m^3 by means of a free-water intake process.

Fig. 58 shows other series of drying rates for the same material carried out under following conditions:

(1) calculation carried out for two-sides drying,

T = 295 ϕ = 30 % RH $\beta = 3 \times 10^{-3}$ m/s on one side
T = 278 ϕ = 90 % RH $\beta = 2 \times 10^{-3}$ m/s on the other

(2) measurements, as above

(3) measured drying in the heat box with T = 330 K. Wetting by means of natural water-intake to $\omega_o = 230$ kg/m^3

(4) as above, wetted in a vacuum chamber with air pressure 10 % of the atmospheric pressure.

(5) measured in the laboratory conditions. Two specimens with different starting moisture contents and 50 % smaller drying surface. Wetted by natural intake.

(6) and (7) drying in the laboratory conditions as above but three-directional drying of a little specimen and a large specimen, respectively.

Figs 55-58 allow a few interesting conclusions. First of all a disagreement between programs may be noted. If a steady drying rate is assumed the amount of moisture being dried is better determined, even though the actual drying process is not approached.

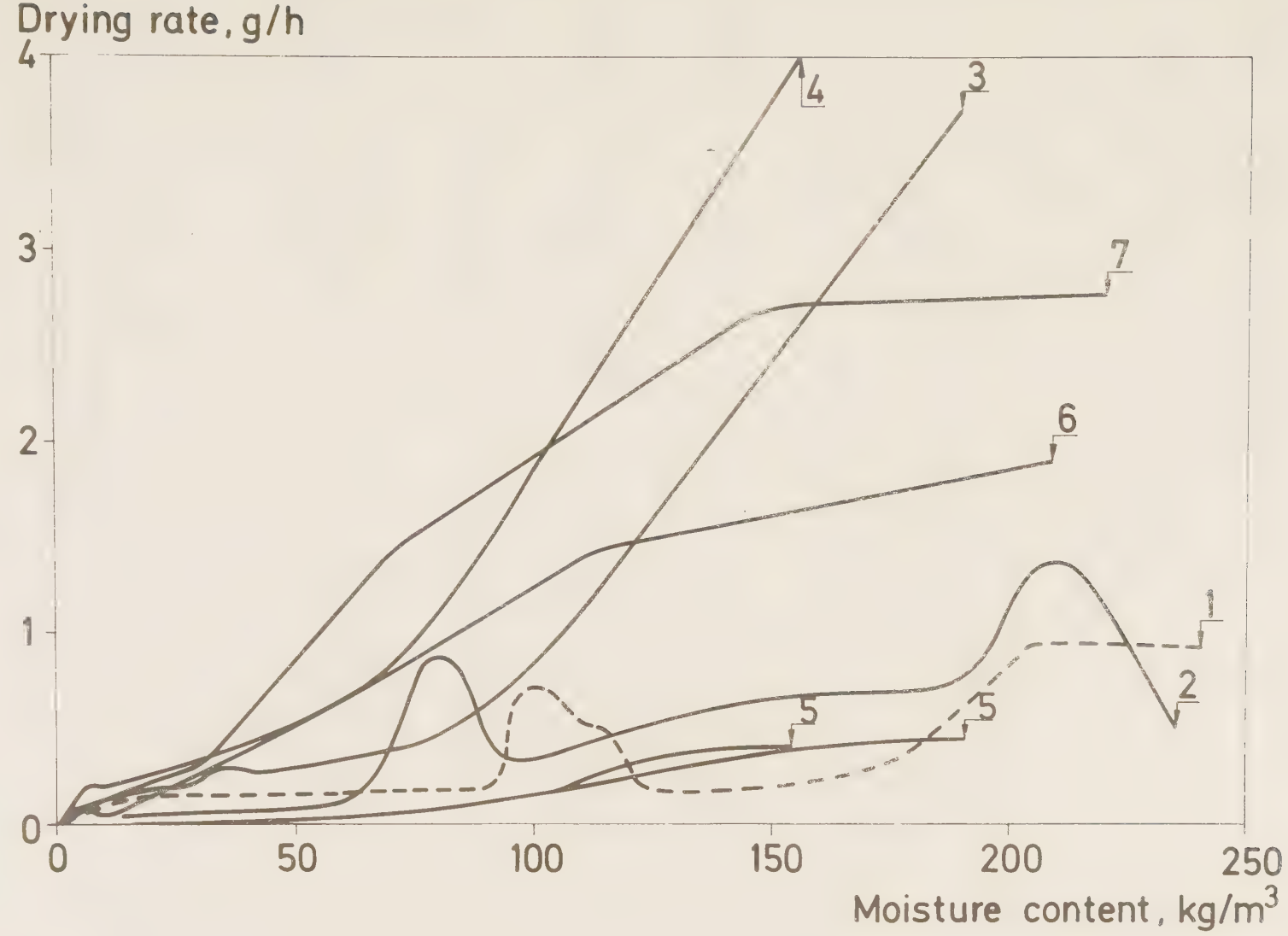

Fig. 58. Drying rate of the clay-bricks according to measurements and calculations. See text.

The second program, based upon a concept of critical moisture content and the first knick point of drying (cf. Vos, 1967), gives a much better description of the drying process and allows for judgement of moisture content distribution.

Figs 57 and 58 show how approximative the calculation model is. The whole drying run seems to be split up in two regions. The drying rate at the end of the first region is lower than the actual, while it is higher than the actual when passing by the knick point moisture content.

The agreement between tests and calculations shown in Figs 57 and 58 is not so good but the following should be remembered:

(i) material properties were determined on several different specimens with non-uniformly distributed moisture at the beginning of the test

(ii) similitude requirements were used in order to compare different specimens

(iii) all shown tests are performed on different specimens and not corrected with regard to the similitude requirements

(iv) capillary hysteresis is included in the above processes

It is therefore not improbable that the model could give better agreement if the material properties were determined in a more acurate way, as it is for instance in practice in the soil science field. During determination of material properties no apparatus for non-destructive measurement of moisture content was available.

The above model is, however, not expected to give an exact description of the drying process, as it is based on the knick point concept. The geometry of the drying system is not accounted for here and as shown in Fig. 58 may also influence the results.

6.6 Drying and wetting in sequences.

Calculations carried out for materials exposed to environmental conditions are not suitable for verification of the SRS-model because too many different simplifications must be used. The faults may originate in the description of the following factors:

(a) Frequency, intensity, duration of rain

(b) Drying conditions: air temperature, vapour concentration air movements, solar radiation etc.

(c) Hysteretic conditions, in particular time-dependent changes in material characteristics.

(d) Material properties: moisture retention and moisture diffusivity curves, capillary saturation.

Even if the calculations discussed below are not used for the verification of the SRS-model, tests and calculations will be compared in order to assess the influence of simplifications in the description of boundary conditions (climatic factors).

The interest here is focused on the wetting by a driving rain, as the drying conditions (including solar radiation) were analysed by Sandberg (1973).

For a roof structure an equivalent air temperature may be used (see Sandberg, 1973).

For a wall, the sun radiation is neglected and the mean day temperature may be based on the air temperature in an annual variation cycle.

The rain conditions are determined by rain time and limiting rain intensity which are included in the input data.

Fig. 59 shows calculations performed for the aerated concrete roof discussed in Fig. 8.1 of Sandberg (1973). The wetting occurs in winter-time due to a condensation, but in summer-time it dries out. Diffusivity used in the calculation is based on Kooi (1971) but corrected in the hygroscopic moisture content range (see Chapter 6.3).

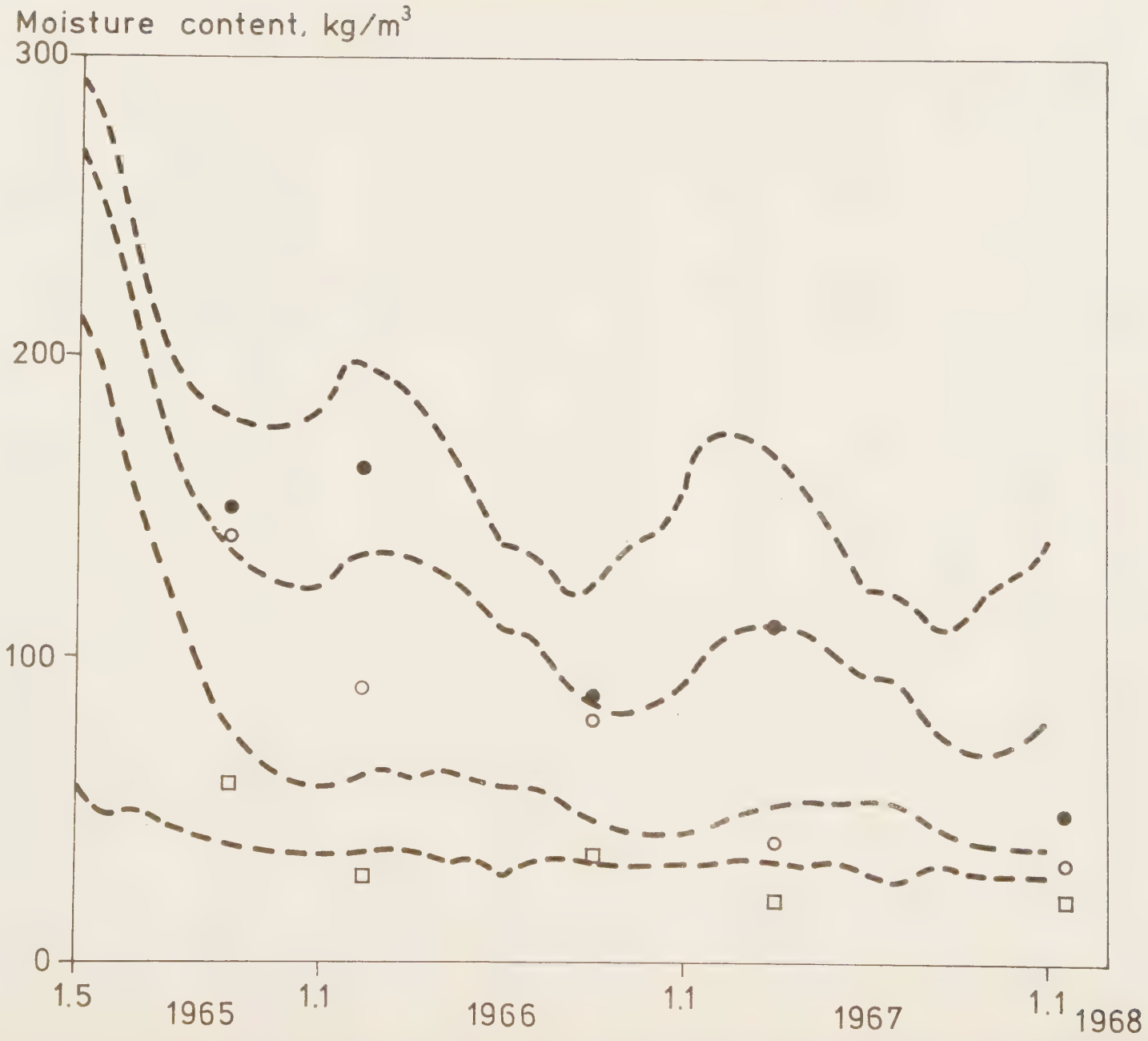

Fig. 59. Measured and calculated moisture contents in 20 cm aerated concrete roof structure. (See Sandberg, 1973)

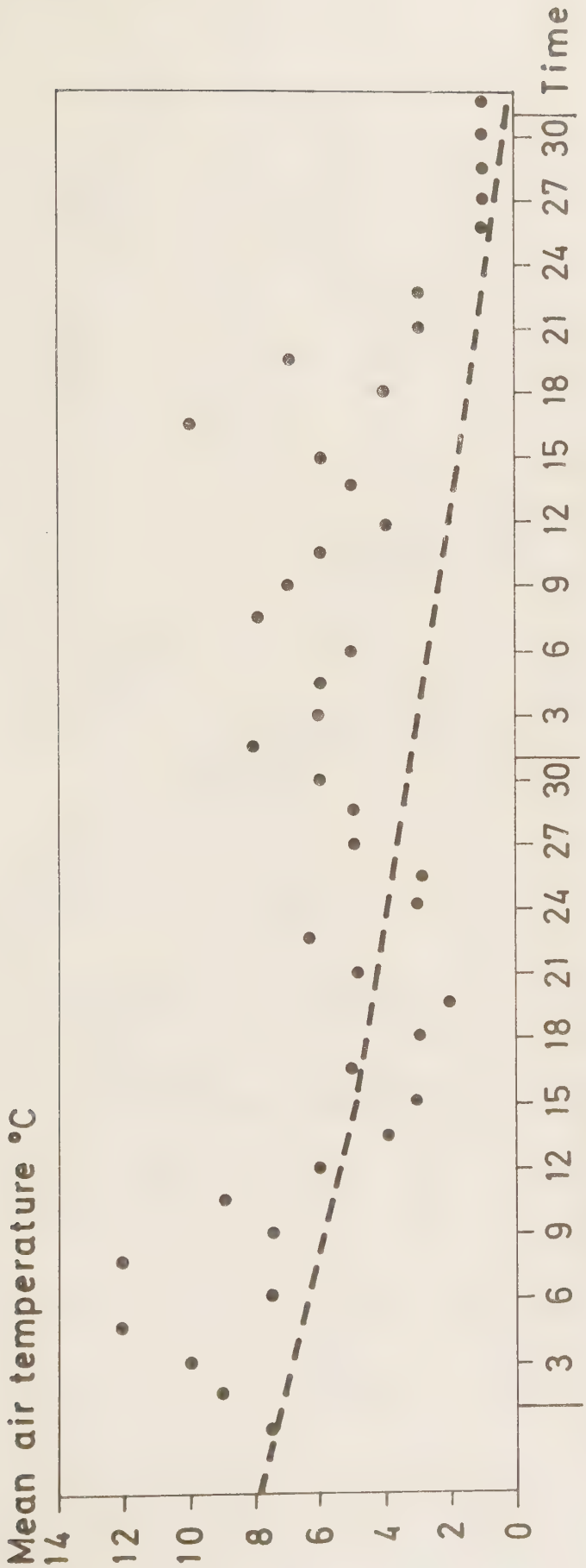

Fig. 60. Real temperature of the outside air and its approximation used in the program.

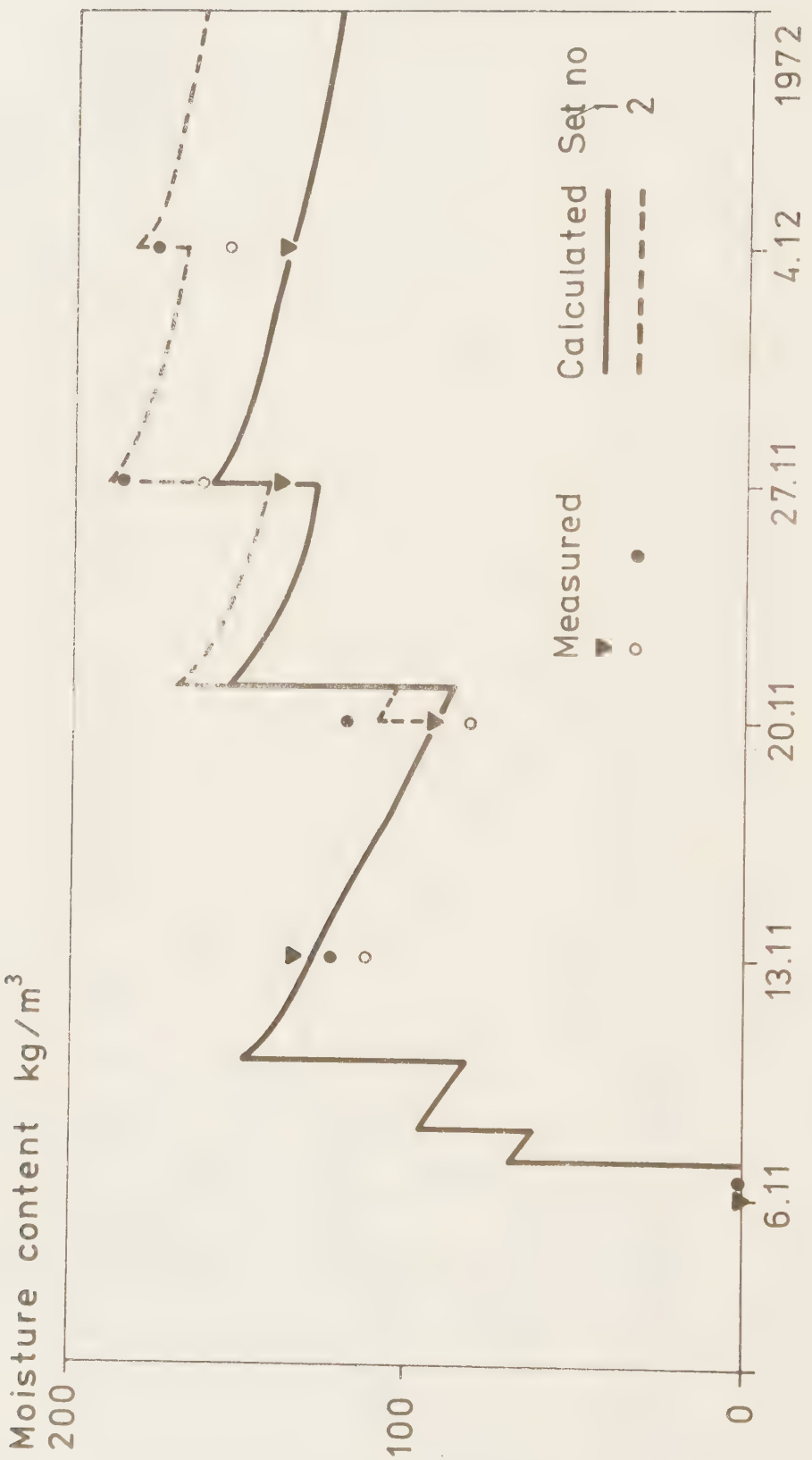

Fig. 61. Measured and calculated moisture content of the initially dry clay-bricks exposed to natural conditions. Two series were examined where the second had additional one-hour-long immersion to water.

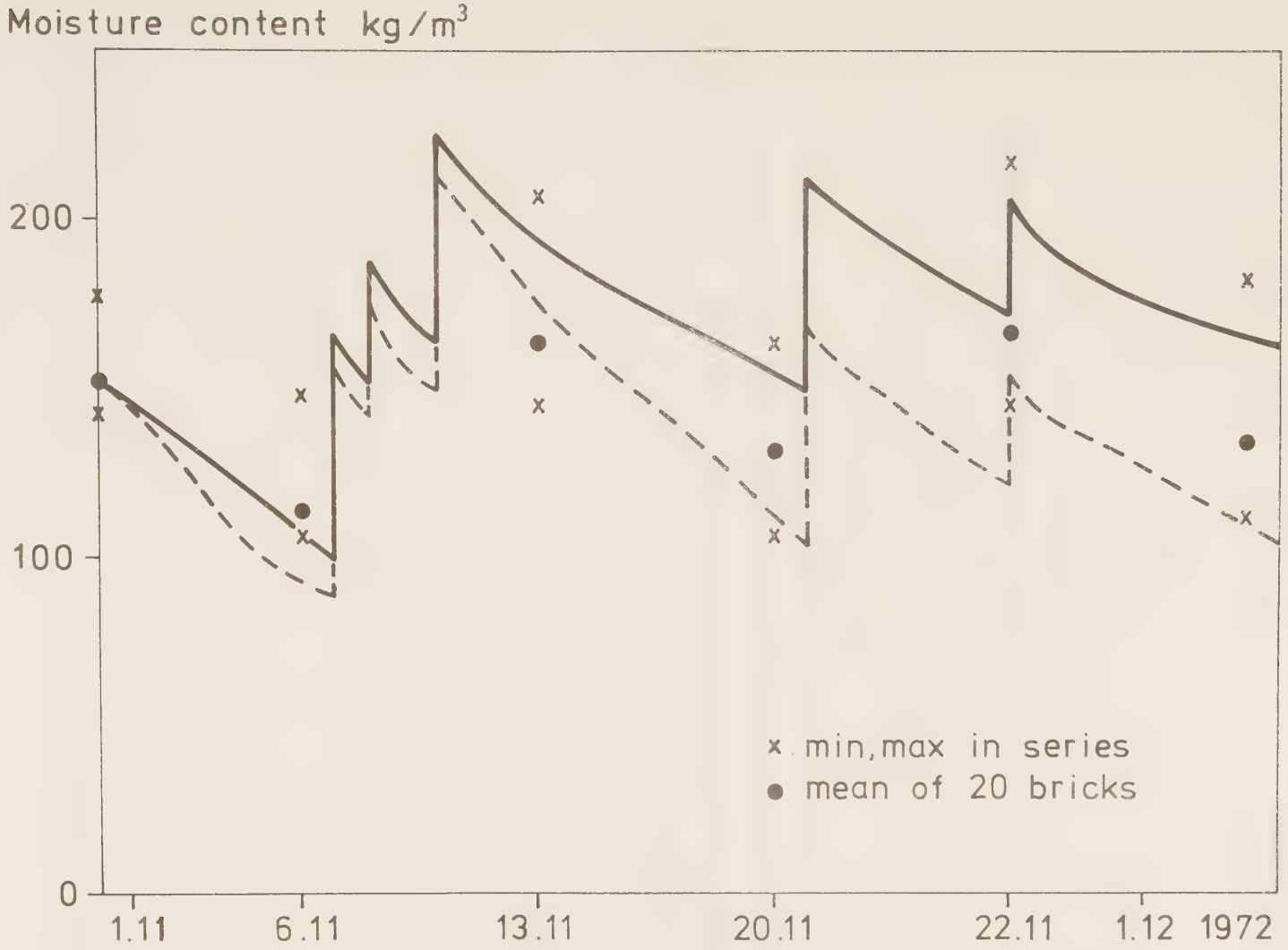

Fig. 62. Measured and calculated moisture content of the initially wet clay-bricks exposed to natural conditions.
— calculated with $\beta = 2.8\times10^{-3}$ m/s -- calculated with $\beta = 5.6\times10^{-3}$ m/s.

In calculating changes of the moisture content of the clay-bricks exposed to real climatic conditions one should be aware how far the actual temperature is from its representation in the program (see Fig. 60).

The significance of snow blown into the rain gauges by driving rain and melting there, is also difficult to assess.

Figs. 61-62 show measurements and calculations of the clay bricks exposed to recorded climatic conditions in November and December 1972.

There were three test series carried out, the first with a starting moisture content about 140-180 kg/m^3, the second with dry specimens at the beginning and natural exposure, the third as above, except that an additional one-hour-long immersion in water was also applied each week. The amount of water intake was recorded.

Fig. 61 shows both series started with the dry specimens, Fig. 62 shows the third series. Calculations shown were carried out for two levels of the surface coefficient of mass-transfer. Actually, this coefficient β is strongly variable and depends on wind velocity. For the sake of simplicity it is used as a constant. In the calculations shown in Fig. 62, surface coefficient of mass-transfer used as follows

(i) $\beta = 2.8\times10^{-3}$ m/s i.e. indoor climate

(ii) $\beta = 5.6\times10^{-3}$ m/s

7 MOISTURE CHARACTERISTICS OF THE POROUS MATERIALS:

7.1 Routine testing.

The great majority of tests performed within building technology and concerning moisture transport or moisture effects like shrinkage, reversible and irreversible deformations, vapour permeability etc. are valid only for the tested specimen.

The usual testing routines are inadequate with regard to the material description, and do not allow any generalization of the test results. Moreover, the material properties are expressed often as a combination of a few physical properties or depend on the procedure used as for instance, the water absorption coefficient, the height of the capillary rise or the moisture retention of fresh mortar.

There is no doubt that the system used in soil science research is much better suited to physical phenomena. In introducing techniques yet not utilized for building materials, one has to face a fundamental question: "What kind of routine may be used for the determination of material properties in a current industrial research program?"

It is not too difficult to determine a given property by testing a few specimens chosen from selected material, but the same question may become extremly difficult if the discussed property should be representative for a given product. There are important problems of: how to reproduce the material structure in order to perform another test and what is the best way to describe the material structure with regard to moisture.

The tested specimens should be adequately described with regard to both moisture and pore-structure of the material, in order to assure the reproducibility of the tests. This may be done by direct measurements of the pore properties or some mechanical tests of the porous structure but it may also be done by means of another (complementary) moisture measurement.

The relative variables, discussed in Chapter 5.3, were shown to give a better description of the tests than the moisture content or suction itself. Therefore, for each material tested with regard to moisture, the

following material properties should be determined:

(a) absolute saturation
(b) capillary saturation
(c) density of the dry specimen
(d) dry-cup vapour permeability (0-50 % RH)
(e) equilibrium moisture content at 50 % RH.

Properties (a) and (b) are necessary for constructing the relative variables. The above list should be considered as the minimum required for a description of the material.

At present, density alone is used. This is insufficient (as for instance shown in Fig. 16.1 of Bomberg, 1971). In fact information about the total open porosity (absolute saturation) and the part of pore volume which is filled by free water (capillary saturation) is always more valuable.

The above listed tests describing the material are easy to perform and the test procedures are briefly described below.

7.1.1 Capillary saturation.

Both water and air transports in this test should be unidimensional. This may be achieved either with water-proof layer on the side surfaces, or by sufficient geometry of the specimens. Thickness of the specimens may vary between 1 and 30 cm depending on the accuracy of weight determination. Evaporation from the upper surface of the specimen may be decreased by a loose foil or rised RH-level in the ambient air. Specimens should not be immersed in water deeper than less of these two limits: 5 % of the thickness or 3 mm. Practically the test involves specimens of 10-15 cm placed on a supporting gauze in a water tank with a steady water level.

A diagram of water intake versus square root of time is drawn as shown in Fig. 19. At least three points should be measured before, and two points after the knick point was observed.

Specimens used for this test should be absolutely dry i.e. dried at 378-383 K or under comparable conditions until the weight is constant.

7.1.2 Absolute saturation.

After testing the capillary saturations, or after immersion in water under atmospheric pressure for a time sufficient to obtain capillary saturation, the specimens are placed in water in the vacuum tank. The vacuum is applied slowly and after several minutes the steady level of vacuum is achieved. The vacuum should be higher than the bubbling pressure of the material under test, but not too high. As the bubbling pressures of usual porous building materials do not exceed 0.6-0.8 atm, it is enough to apply vacuum producing e.g. 0.9 atm pressure difference between air in the tank and the atmospheric air.

7.1.3 Equilibrium moisture content at 50 % RH

This test should be performed if the sorption isotherm for the material is not tested. It is necessary to start drying from the absolute saturation and to continue until a constant weight is reached at room temperature, and about 50 ± 2 % RH. The room temperature may vary a few degrees during the tests but the relative humidity should be kept as steady as possible.

7.1.4 Dry cup vapour permeability.

This may be tested in the same room as the equilibrium moisture content at 50 % RH. Tested material should be absolutely dry prior to the test. The test procedure is described in numerous reports. (See Joy & Wilson, 1965.)

If the wet-cup permeability is simultaneously determined, which can be easily done in the same room, the tested material should be absolutely saturated prior to the test.

7.1.5 Similitude requirements.

If a complete description of the material properties related to moisture is required, all the drying and wetting moisture retention as well as the moisture conductivity curves need to be determined as functions of moisture content. (Cf. Similitude requirements: Corey & Corey, 1967, or Bomberg, 1972.)

As the absolute minimum four material properties above discussed is required. They produce only three points on a moisture retention curve and one point on a conductivity curve. These tests cannot prove whether the tested material is identical with respect to moisture. They may, however, clearly show whether the tested materials are different.

Finally, the following tests should be considered essential if the full set of moisture properties is required:

(a) Isothermal free-water intake tests of a few of the specimens. These specimens are later placed in a vacuum container and the absolute saturation is determined.
(b) Another series of tests where density, capillary and absolute saturations are determined on a statistically representative basis.
(c) Isothermal drying tests where both average moisture content and a few moisture distributions at different time of drying are determined. The diffusivity curve is calculated.
(d) Sorption isotherms for absorption and desorption i.e. moisture equilibria for $\phi \leq 98$ % RH by means of weighing.
(e) The drying water retention curve by means of pressure or vacuum plates i.e. moisture equilibria for $\phi > 98$ % RH.
(f) Vapour permeability (dry and wet-cup methods) and possibly the hydraulic conductivity by the water filtration techniques.

The amount of work involved in determining of a complete set of the material properties relating to moisture is almost impossible to predict, as these properties are notably variable. This work may be reduced if different measuring techniques are used e.g. related to the vapour phase or total moisture transfers.

It was also pointed out (Roqowski, 1972) that the material property at some points (e.g. capillary saturation) plays a more decisive role than

the slope of the curve between them.

In order to appropriate the equilibrium state, 2-4 weeks are needed for a single measurement, and in order to complete a set of material properties data, 3-4 months may be required even if some measurements are conducted simultaneously.

Although this may seem troublesome, it does provide a real basis for calculation of the moisture transport in porous materials for any climate and a basis for correlation between moisture content and different effects of moisture like shrinkage, other deformations due to moisture, frost resistance etc..

7.2 Moisture equilibria

The water retention curve indicates the energy of a certain volume or water being in equilibrium with the pore-structure of the material. The moisture retention curve contains the hygroscopic region where measurements are usually performed by means of the sorption balance and the capillary water region where measurements are carried out on the liquid phase by means of pressure or vacuum plates.

Two retention curves should be determined if accurate calculations are to be made: one of these would relate to wetting from absolute dryness to at least the capillary saturation, the other to drying from the absolute saturation to the moisture content at the lower boundary of the calculations. The moistening hysteresis may be evaluated by a comparison of those two retention curves.

Similarly osmotic suction may be determined by a comparison of a different pair of retention curves, namely those based on measurements carried out during utmost drying of the "fresh" specimens and of specimens where soluble salts were already removed.

There are several sorts of moisture retention curves. The basic one is the utmost drying retention curve. The retention curve describes the level of the energy of the pore-water filling a certain pore volume related to the mass of the water. A derivative of this function gives a

material property which is called here the differential moisture capacity and which has been called in some other reports the pore-distribution index. Testing procedures reported in Ahlgren (1972) for the hygroscopic region and Bomberg (1972) for the capillary water region are omitted here. Fig. 6 and Figs 63-64 provide examples of the moisture retention curves.

7.3 Moisture diffusivity and conductivity curves.

Depending upon the experimental facilities either moisture conductivity or moisture diffusivity is experimentally determined, the other one may be calculated if the differential moisture capacity is known.

The conductivity coefficient is much better defined with regards to its variability. Works of Brooks & Corey (1964) and other research carried out at Colorado State University suggest that a logarithm of conductivity produces a linear function if the logarithm of moisture content (degree of saturation) is used as the independent variable. Even if this observation is not used during the calculations of moisture transfer (the diffusivity coefficient is both tested and used for calculations), the test results should be recalculated into the conductivity curve and expressed in a double logarithmic plot.

Fig. 65 shows a typical moisture conductivity curve where the level above the bubbling point ($S_b \approx 0.75$) is nearly constant.

The results of experiments may, however, deviate from the above illustrated linear relationship if other factors influence the measurements.

Fig. 66 shows tests on standard gypsum carried out in pressure cells. Two series of fresh specimens were started at different levels of moisture content. The broken line represents an assumed curve if all the soluble salts were already removed (see Bomberg, 1971).

This figure demonstrates that the time factor must be adequately treated for different tests, particularly if the salt content (or the air content) in the specimen may be changed during the tests. For these reasons the pressure plate technique was not frequently used for determination of the

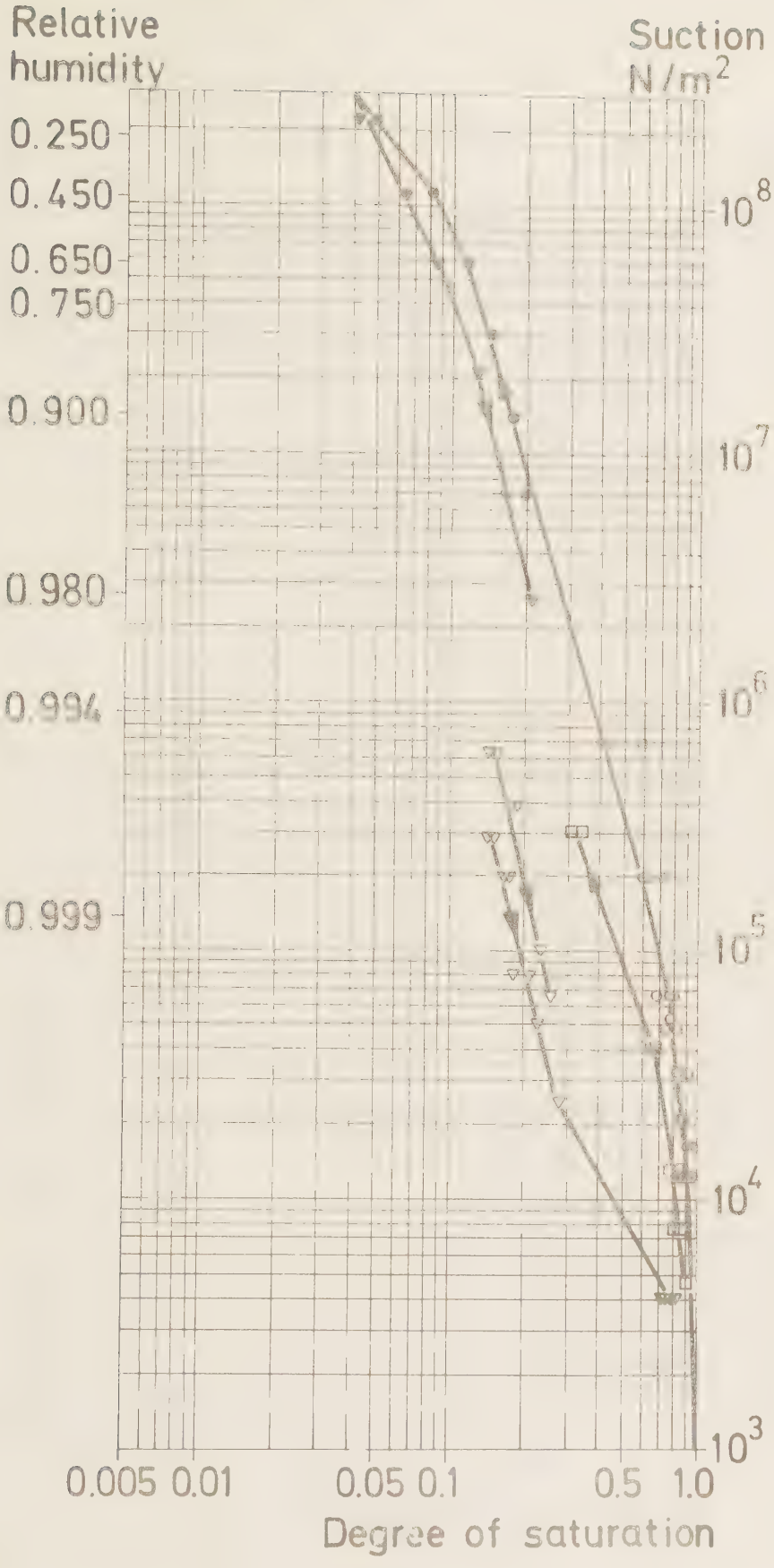

Fig 63. Moisture retention curves for wood-fibre board

- ○ fresh specimens with density 600 kg/m³
- □ ▽ with soluble salts partly removed, density 600 kg/m³
- ● ▼ fresh specimens with density 980/m³, tests of Ahlgren (1972).

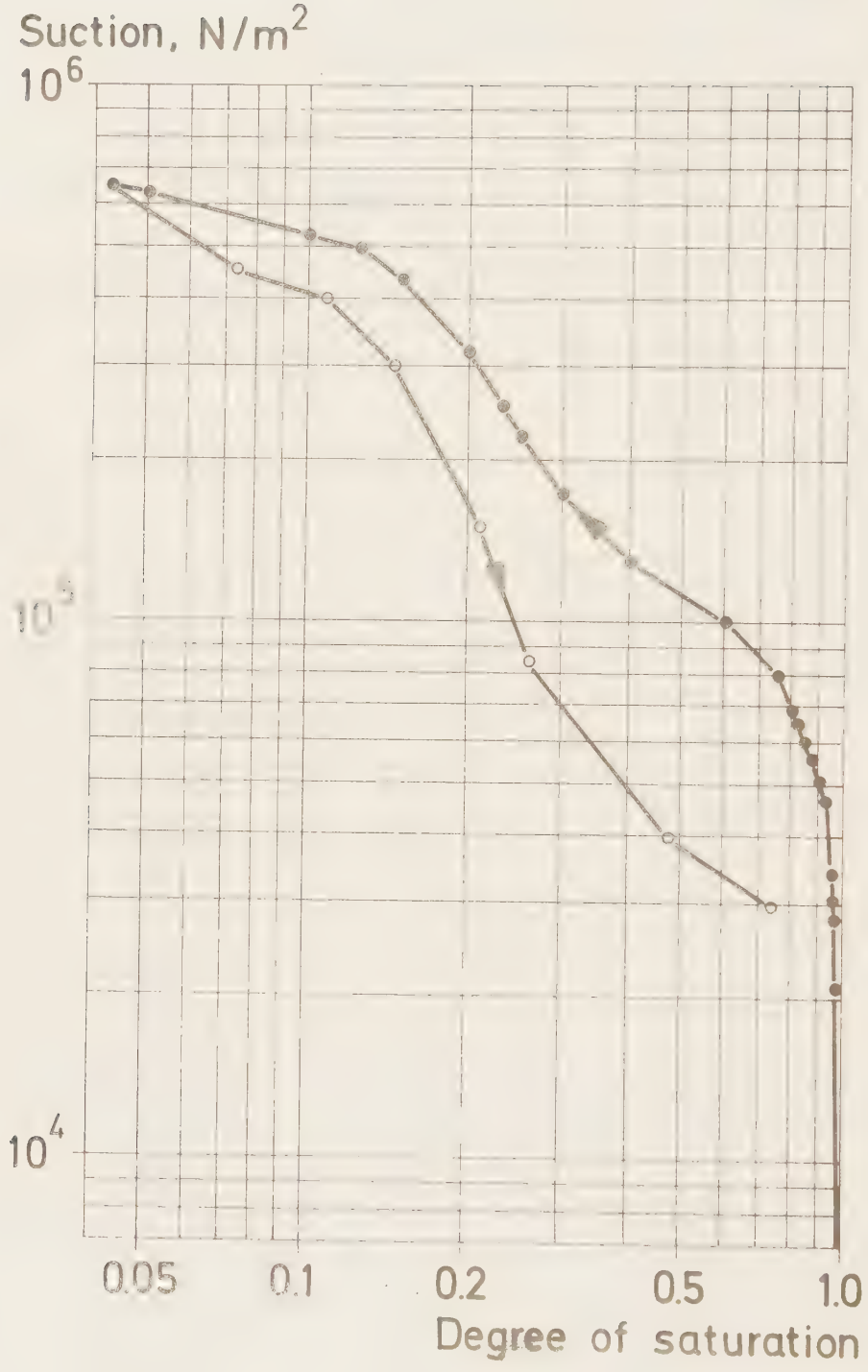

Fig. 64. Drying and wetting retention curves for gypsum specimens with soluble salts removed.

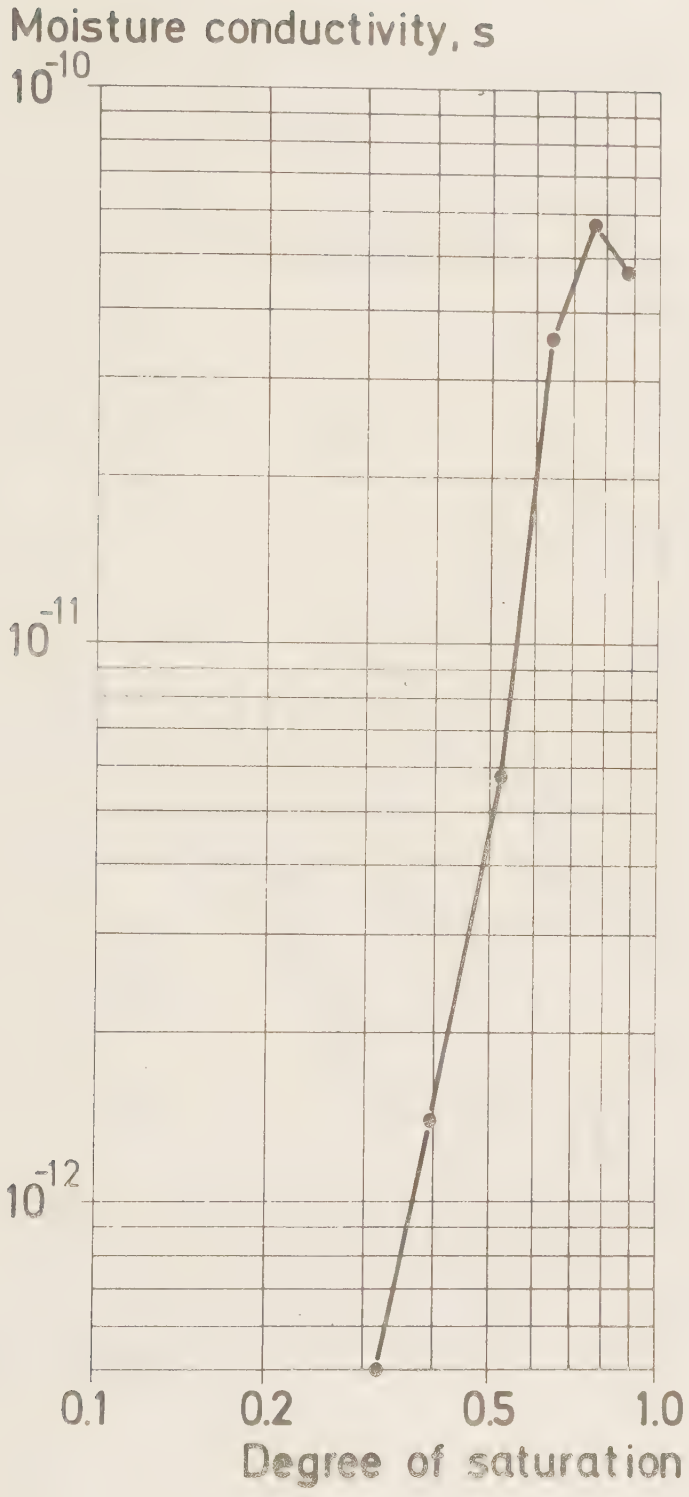

Fig. 65. Moisture conductivity of the clay-bricks with open porosity about 0.34 m^3/m^3.

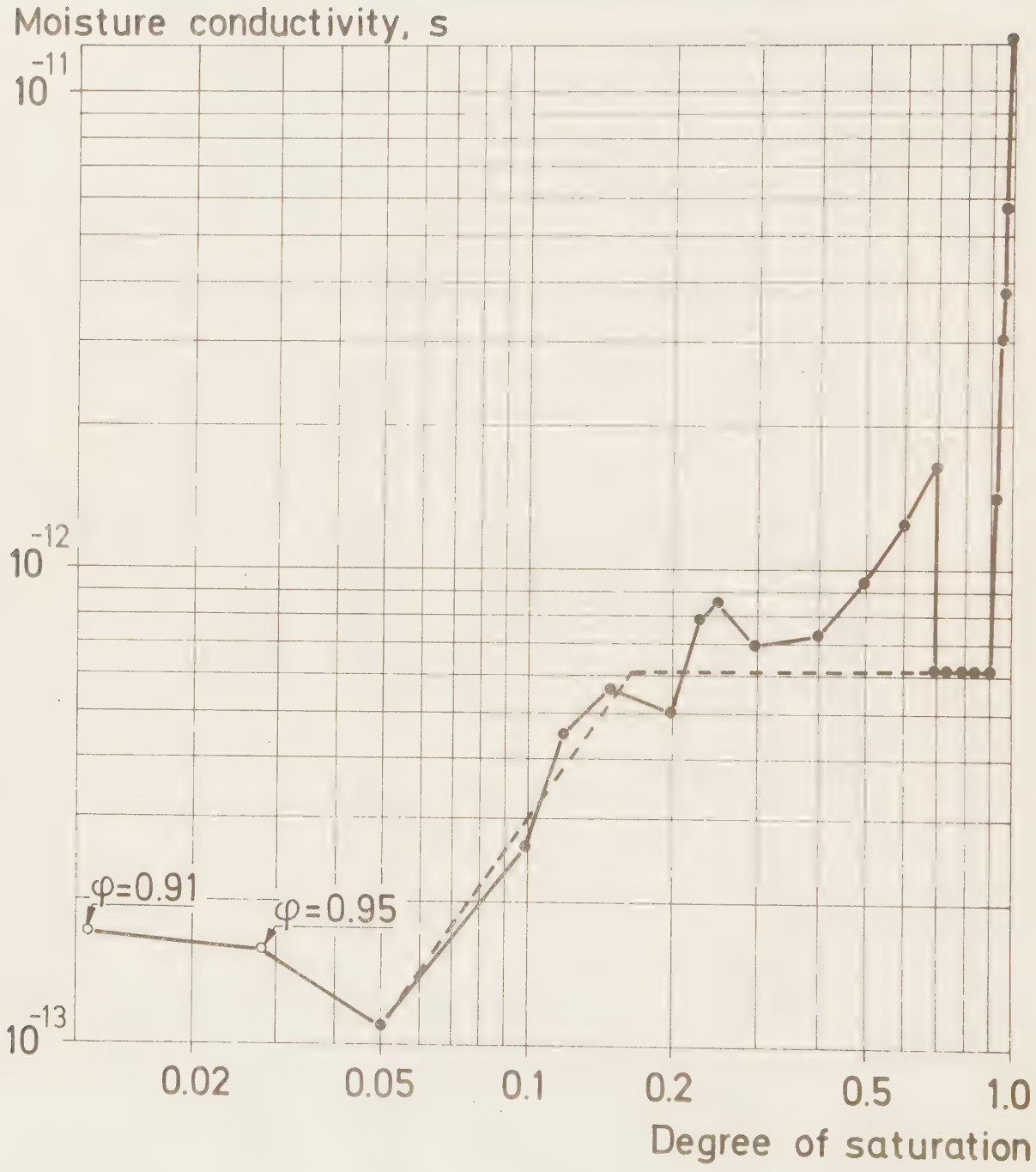

Fig. 66. Moisture conductivity of the standard gypsum. See text.

transport coefficient. It is usually determined by a comparison of different moisture content distributions during drying. Moreover the starting moisture content and density of the specimen must be known.

If the starting moisture content is lower than the absolute saturation, a correction as discussed in Chapter 5.6, may be applied. Tests for calculation of diffusivity coefficient, however,should not be started at a moisture content lower than the capillary saturation.

It is difficult to predict the transport coefficient as a function of moisture content. Fig. 67 which develops a presentation of Rose (1963), may help in better understanding of different types of moisture flows which result in alteration of the diffusivity curve. Examination of Fig. 67 reveals the following stages of saturation.

Stage 1. Molecular adsorption.

Vapour is adsorbed by dry surfaces of the pores. It is difficult to discuss the transport coefficient. Usually it is obtained by extrapolation of the stage 2, which starts at the limit of calculations for the SRS-model.

Stage 2. Water vapour diffusion.

Mainly equimolar vapour diffusion. Some condensation and evaporation in micropores takes place as well as effusion but these may be disregarded. Moisture conductivity coefficient: a constant vapour conductivity (usually tested by the dry-cup method).

Stage 3. Transport in series.

Capillary condensation produces some unmovable water drops. Evaporation from these drops, vapour transport and condensation at the next place usually increases the rate of transport. Moisture conductivity coefficient: an increasing vapour conductivity (usually tested by a narrow range wet-cup method).

Stage 4. Parallel transport.

Absorbed layer in some separate capillaries is thick enough to start local flow of water.

Stages 3 and 4 are difficult to distinguish from the whole region of WVT (water vapour transmission). When it is possible to see a boundary between them, it may be called an upper hygroscopic condensation boundary. Moisture conductivity coefficient: as above.

Stage 5. Unsaturated water flow.

The layer of water absorbed by the capillary walls becomes thick enough to start a thoroughfare transport of liquid water.

It is difficult to distinguish this stage from the combined vapour/liquid transport discussed as WVT in stage 4. The limit called critical moisture content represents the moment when the liquid phase flow has the same density rate as the vapour phase flow.

Moisture conductivity coefficient: an increasing moisture (water) conductivity often called the capillary conductivity. Linear dependence in a double logarithmic diagram. Tested by infiltration techniques with regard to both water and air pressures (Soil Analysis 1965) or recalculated from diffusivity and differential moisture capacity measurements.

Stage 6. Saturated water flow.

The absorbed layer has become so thick that some smaller capillaries are completely filled with water. A direct air transfer is no longer possible. Air bubbles entrapped inside the larger macropores are surrounded by the flowing water. This kind of flow starts during the wetting run at the capillary saturation. If drying from absolute saturation is discussed, this boundary between saturated and unsaturated flow may occur at a somewhat higher moisture content. This region is called either the saturated flow region (Zaslawsky, 1964) or unsaturated flow region (Philip, 1957). In the last case the saturated water flow is considered at 100 % (exactly) of water content, i.e. without any air entrapment.

Moisture conductivity coefficient: nearly constant on two different

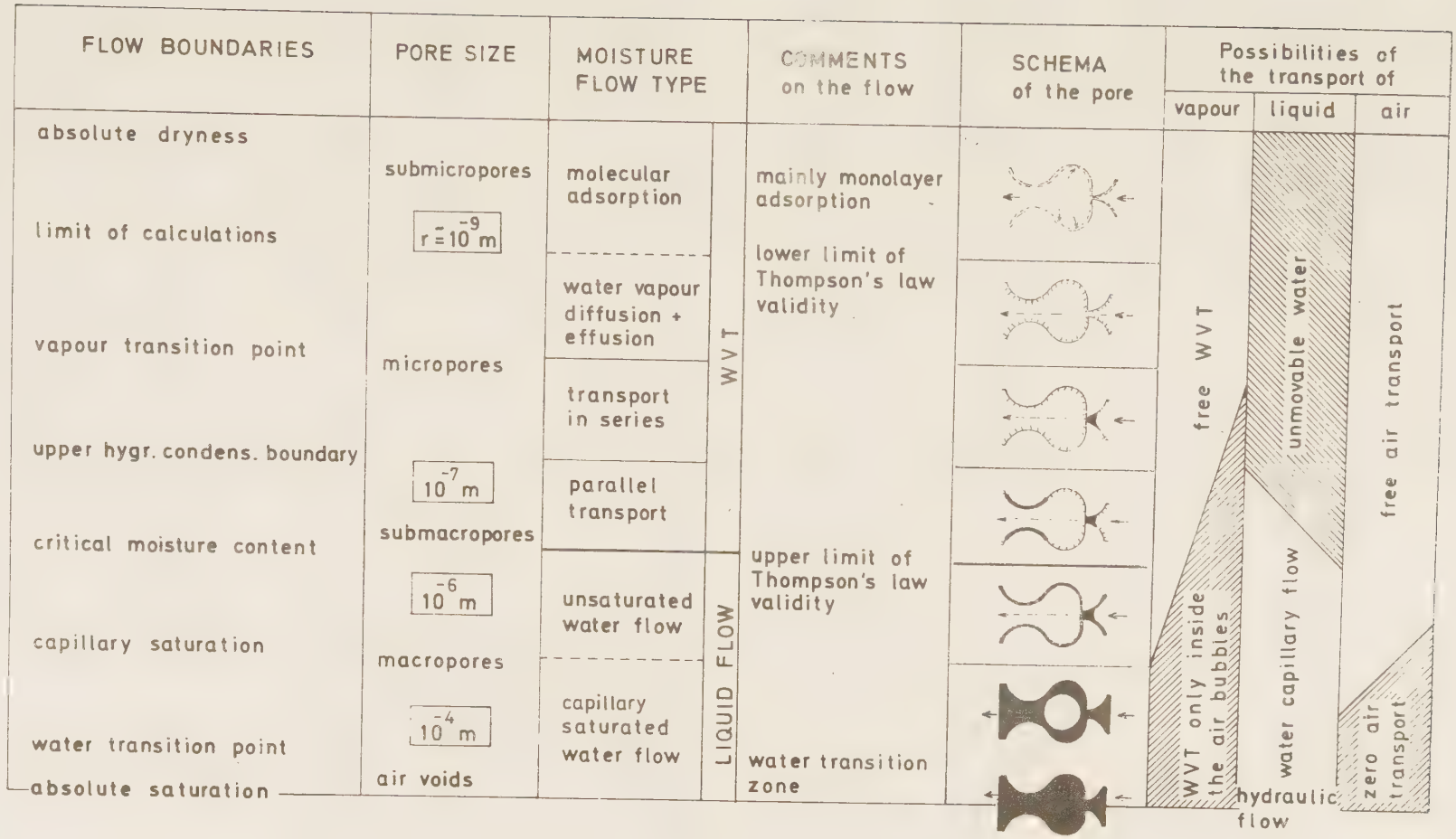

Fig. 67. Different kinds of moisture flow through porous materials.

levels: a capillary conductivity and a saturated hydraulic conductivity. There is a sharp jump from one to the other level in a region called the water transition zone.

For a wetting run without external forces the capillary conductivity level assumed as constant may be used (Brooks & Corey, 1964). The transition zone is, however, observable in a moisture profile during a vertical infiltration (Gupta & Staple, 1964) Testing procedure for determination of conductivity at the saturated (hydraulic) flow involves water overpressure.

Above discussed stages of saturation are visible in the moisture properties of aerated concrete shown in Fig. 15, where WVT (water vapour transmission) clearly shows stages 3 and 4 with incresing and decreasing diffusivity. At about a moisture content of about 50 kg/m^3, the unsaturated water flow region starts. The vapour flux becomes less than the liquid water flux. Capillary saturation for this material, was found in other tests to be about 300 kg/m^3. Above this level, the flow may be considered as capillary saturated.

Other tests performed on aerated concrete (Kooi, 1971, Nielsen, 1973) show the moisture diffusivity decreasing and increasing in the 6th stage, and two clear turing points in the moisture diffusivity curve are visible.

It is assumed that for a material with nearly constant size of the pores, a sharp up- and -down diffusivity curve would be characteristic, while a linear pore-size distribution would produce a nearly continous increase of the diffusivity.

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A P P E N D I X

FORTRAN PROGRAM NUMBER 2

```
      DIMENSION RHO(100),RAM(100),DE(30)
      DIMENSION TMI(360),TME(360),CVMI(360),CVME(360)
      DIMENSION P(400),D(400),DWT(400),HK(400),W(400)
      DIMENSION D1(30),R(5),P1(30),W1(30),W2(30),W3(30)
      DIMENSION TPE(360),TM1(360),CVME(360),CVM1(360)
      INTEGER TIME,SETT,W,W1,OF,DMORY,DWETT,DAY
      COMMON DPIN,JMAX,NC,DAY
C     THIS IS PROGRAM NO 2
C     ZSURF MEANS SURFACE RESISTANCE E.G. COATING ON MATERIAL
C     CALCULATIONS MUST GO FROM 1 SIDE TO E SIDE (T1,W1 TO  TE,WE)
C     POTENTIAL EQUATION SOLVED BY EXPLICITE METHOD WITH NON-CONTROLLED
C     LINEARISATING CONST , THERMALLY DRIVEN FLOW ADDED AS SEPARATE PART
C     TEMP FIELD IS STATIONARY FOR ONE PERIOD S COUNTED IN SECONDS
C     BOUNDARY AND CONTACT PLANE IN SUCTION,INSIDE THE MATERIAL IN MOIST CONTENT
C     REAL SUCTION IS NEGATIV,P IN CALC IS POSITIVE
C     THE CAPILLARY SATURATION IS AT INDEX NC,BETWEEN RECORDINGS STEP IDELTA
C     DRYEND:END OF CALCULATIONS WHERE UNDST HYSTERETIC LOOPS MEET EACH OTHER
C     DRYABS:ABSOLUTE SATURATION,LAST DATA EXCEED IT ONLY FOR PRACTICAL WRITING
C     CRITICAL MOISTURE CONTENT CRITW OCCURS AT THE NCRW
C     MOISTURE CONTENT IN KG/M**3, STEP IN 1 UP TO 25*IN 5 STEP,ABOVE 10 STEP
C     NTIME MEANS THE ACTUAL TIME IN SECONDS,TIME MEANS THE RECORDING TIME,SEC
C     DPC IS POSITIVE AT THE WETTING RUN,DRYING RATE AT THE DRYING RUN
C     NUMBER=2 IF WATER SUPPLY IS LIMITED,LOOP=1 IF FIRST DRYING LOOP IS TESTED
      CVS(T)=(4.60+3.43*((T-273.0)/10.0)+0.96*((T-273.0)/10.0)**2+
     *0.10*((T-273.0)/10.0)**3+0.020*((T-273.0)/10.0)**4)/1000.0
      ER=EM/DX
      EA=EN/DX
      DAY=IFIX(TIME/86400)
      IF(DAY.GT.360) DAY=DAY-360
      NO=2
      WRITE(6,110) NO
  110 FORMAT(1X,' THIS IS PROGRAM NR ',I5)
      CALL LIN(W)
      CALL ELIN(P)
      CALL ELIN(D)
      CALL ELIN(DWT)
      CALL ELIN(HK)
      CALL TEMP(TM1)
      CALL TEMP(TME)
      CALL VAPOR(CVMI)
      CALL VAPOR(CVME)
      READ(5,55) ICONST
   55 FORMAT(1A,I1)
      WRITE(6,55) ICONST
      READ(5,5) RTI,RTE,RCVI,RCVE
    5 FORMAT(1X,4E5.1,2E7.3)
      WRITE(6,5)RTI,RTE,RCVI,RCVE
      IF(ICONST.EQ.1) GO TO 660
      DO 130 DAY=1,360
      TMI(DAY)=RTI
      TME(DAY)=RTE
      CVMI(DAY)=RCVI
      CVME(DAY)=RCVE
  130 CONTINUE
  660 CONTINUE
      READ(5,111) DMIN,DMAX,INC,NCRW
  111 FORMAT(5I5)
      READ(5,54) LL
      WRITE(6,54) LL
      DO 103 K=1,LL
      READ(5,113) IRDAY(K),IRTIME(K)
      WRITE(6,113)IRDAY(K),IRTIME(K)
  103 CONTINUE
   54 FORMAT(I10)
      READ(5,54) ISTART
      READ(5,54) LASTD
      SDUT=LASTD*86400
   11 FORMAT(1X,'STARTING AND THE LAST DAYS ',2I10)
      WRITE(6,11) ISTART,LASTD
    1 FORMAT (10 F8.1)
      IF(LASTD.GT.360) LASTD=360
      WRITE(6,1)(TM1(DAY),DAY=ISTART,LASTD)
      WRITE(6,17)(CVMI(DAY),DAY=ISTART,LASTD)
      WRITE(6,1) (TME(DAY),DAY=ISTART,LASTD)
      WRITE(6,17)(CVME(DAY),DAY=ISTART,LASTD)
C     DAYS FROM THE START OF THE CALCULATIONS,RAIN DURATIONS IN SECONDS
      WRITE(6,112)DMIN,DMAX,INC,NCRW
  112 FORMAT(1X,'DMIN=',I3,3X,'DMAX=',I3,3X,'INC=',I3,3X,'NC/NCRW=',I5,I5)
      WRITE(6,16)(W(J),J=1,DMAX)
   16 FORMAT(10I5)
      WRITE(6,17)(P(J),J=1,DMAX)
   17 FORMAT(1H0,10E8.2/  (10E8.2))
      WRITE(6,17)(D(J),J=1,DMAX)
      WRITE (6,17) (CAT(J),J=1,DMAX)
      WRITE(6,17)(HK(J),J=1,DMAX)
      READ(5,115) IDWET,IDDRY
  115 FORMAT(2I10)
      WRITE(6,115) IDWET,IDDRY
  115 FORMAT(1X,'IDELTA FOR WETTING =',I5,5X,'FOR DRYING =',I7)
      READ(5,115)DWET,DMORY
      WRITE(6,116) DWET,DMORY
  116 FORMAT(1X,'TIME STEP FOR WETTING=',I5,5X,'FOR DRYING=',I5)
      READ(5,54) Y
      READ(5,2) BWETI,BWETE
      WRITE(6,117) BWETI,BWETE
  117 FORMAT(1X,'BETA DURING WETTING - INSIDE=',E6.2,5X,'OUTSIDE=',E6.2)
    2 FORMAT(2E6.2)
      READ(5,2) BDRYI,BDRYE
      WRITE(6,118) BDRYI,BDRYE
  118 FORMAT(1X,'BETA DURING DRYING  - INSIDE=',E6.2,5X,'OUTSIDE=',E6.2)
      READ(5,6)DA
    6 FORMAT(E6.2)
      READ(5,6) DR
      WRITE(6,200)DA
  200 FORMAT(1X,'AIR AVERAGE DIFFUSIVITY',E6.2)
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      WRITE(6,201) QR
  201 FORMAT(1X,' LIMITING RAIN INTENSITY IN KG/M**2 HOURS ',E6.2)
      READ(5,3) (W1(K),K=1,M)
    3 FORMAT(10I5)
      WRITE(6,13)(W1(K),K=1,M)
   13 FORMAT (1X,'START M C  ',10I5)
      READ(5,4)DX
    4 FORMAT(E5.3)
      WRITE(6,14)DX
   14 FORMAT (1X,'DX=',E5.3)
      READ (5,204) RI,RL
  204 FORMAT(2E5.3)
      WRITE(6,205) RI,RL
  205 FORMAT(1X,'SURFACE HEAT RESISTANCES IN=OUT ',E5.3,2X,E5.3)
      MM=M-1
      AWMAX=FLOAT(W(JMAX))
      AWMIN=FLOAT(W(JMIN))
      CAPW=FLOAT(W(NC))
      CRITW=FLOAT(W(NCRW))
      BS=0.001
      TS=293.0
      STANDG=CVS(TS)*BS
      C55=0.0
      EPS=0.000000001
      SEPS=0.01
      DMAX=D(JMAX)
      DMIN=D(JMIN)
      DCAPW=D(NC)
      DCRITW=D(NCRW)
      ZSURF=0.0
      DO 24 K=1,M
      QL(K)=1
      J=W1(K)/IN
      IF (J.LT.JMIN) J=JMIN
      IF (J.GT.JMAX) J=JMAX
      P1(K)=P(J)
      W2(K)=FLOAT(W1(K))
      WM=WM+W2(K)
   24 CONTINUE
      WRITE(6,9)(P1(K),K=1,M)
    9 FORMAT(1X,'START SUCTION ',10E8.2)
      AK1=WM/M
      AK2=AK1
      WSTART=AK2
      IFLAG=1
      DMNEW=0.5*DX**2/DMAX
      DMWET=DMNEW
      DH=DMNEW
      IDELTA=IDDMY
      ER=DH/DA
      EA=ER/.5
      BETAI=BDRY1
      ABC=ZSURF+1.0/BETAI
      BETAI=1.0/ABC
      BETAE=BDRYE
      ITURN=1
      NEWS=1
      NUMBER=1
      CORRW=1.0
      LOOP=1
      JST=IFIX(WSTART/IN)
      DSTART=D(JST)
      FLUXI=EPS
      QMAXI=FLUXI
      X=0.5*10**7
      ZRAND=DSTART/DCAPW
      IF(ZRAND.LT.1.0) ZRAND=1.0
      IF(ZRAND.GT.2.0) ZRAND=2.0
      IF(LSTART.GT.DCAPW) DSTART=DCAPW
      NSTEP=1
      NTIME=TIME
      KTIME=NTIME-1
      NHOUR=0
      DAYS1START
      IBEGINTIME*60
      IDK=0
      DELTAW=AWMAX-AWMIN
      WTURN=AWMAX
      IF(AK2.GT.CRITW) WTURN=AK2
      IF(AK2.GT.CAPW) WTURN=CAPW
      CORRZ=DELTAW/(AIRA-DWMIN)
      CORCAP=DELTAW/(CAPA-AWMIN)
      IRAIN=0
      CAPSAT=CAPW
   25 CONTINUE
      IF(NTIME.LT.KTIME) GO TO 33
      KTIME=KTIME+
      DAY=DAY+1
   30 CONTINUE
      DAY=DAY-NN*360
      TI=TMI(DAY)
      TE=TME(DAY)
      IF(IFLAG.EQ.1) CVI=CVMI(DAY)
      CVE=CVME(DAY)
      TI=TI+
      RR=R1+RE
      DO 27 K=1,M
      IF (J.LT.JMIN) J=JMIN
      IF (J.GT.JMAX) J=JMAX
      R(K)=DX/RR(J)
   27 RR=RR+
      Q=TT/RR
      K=1
      DT(K)=(R1+R(K))*Q
      DO 29 K=2,M
   29 CONTINUE
      TXI=TI-XU
      BI=CVS(TI)
      FII=CV
      IF(FII.LT.SEPS) FII=SEPS
      FIE=CVE/BE
      IF(FIE.LT.SEPS) FIE=SEPS
      CB=1.0 - 0.00001
      IF(FII.GE.CB) SLNI=0
      IF(FII.LT.CB) SLNI=ALOG(FII)
      IF(FIE.GE.CB) SLNE=0
      IF(FIE.LT.CB) SLNE=ALOG(FIE)
      RI=.5*RI*SLNI
      RL=.5*RL*SLNE
      X=-RI
      CALL EXPER(X,EXP)
      WI=Y
      X=-RL
      CALL EXPER(X,EXP)
      WE=Y
      K=1
   33 CONTINUE
      NTIME=NTIME+DH
      IF(NTIME.GT.IAA) GO TO 105
   26 CONTINUE
      IF(NTIME.EQ.IBC) GO TO 104
   28 CONTINUE
      IF(CVI.LT.CB) GO TO 340
      IRAIN=IRAIN + DH
      C66=SQRT(IRAIN)
      C55=C55*C66
      GO TO 350
  340 CONTINUE
      IRAIN=0
      C55=0.0
      CAPSAT=CAPW
  350 CONTINUE
      WI=WI+C55
      IF(WI.GT.CAPSAT) CAPSAT=WI
      WIDE=
      INDIC=M
      K=1
      B=W2(K)
      DO 40 K=1,MM
      JP=IFIX(B*CORRW/IN)
      IF(JP.GT.JMAX) JP=JMAX
      WP(K)=W2(K)
      KK=K+1
      DTC=DT(K)
      DCWP=DT(K)
      IF(JP.LT.JMIN) JP=JMIN
      IF(JP.GT.JMAX) JP=JMAX
      IF(LOOP.EQ.1) JP=JMAX
      DAKTW=D(JP)
      DC=DAKTW*EA
      IF(DC.GE.0.2) INDIC=INDIC + M
      IF(DC.LT.0.03) INDIC=INDIC -1
      DWTC=DWT(JP)*EA
      IF (K.GT.1) GO TO 39
      IF(IFLAG.EQ.9) GO TO 38
      JA=IFIX(B/IN)
      IF(JA.GT.JMAX) JA=JMAX
      RAND=1.0
      PXI=P(JA)
      C11=PXI/(RGM*TXI)
      FIXI=EXP(C11)
      IF(FIXI.LT.0.1) FIXI=0.1
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C
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      LTIME=NTIME+60*DH
      ER=DH/DX
      EA=ER/DX
      INDIC=M
      KONTR=1
      GO TO 45
  102 INDIC=M
      IF(NTIME.LE.LTIME) GO TO 45
      IF(IFLAG.EQ.9.AND.DH.GT.120) GO TO 45
      IF(DH.GT.1150) GO TO 45
      DH=DH*3
      IJK=IJK+1
      MIJK=IFIX(IJK/100)
      IJK=IJK-MIJK*100
      KAL(IJK)=NTIME
      KAB(IJK) = DH
      IKMAX=IJK
      ER=DH/DX
      EA=ER/DX
      GO TO 45
  104 CONTINUE
      IDAY=NTIME/86400
      IHOUR=NTIME/3600
      NMONTH=IDAY/30
      NDAY=IDAY-30*NMONTH
      NHOUR=IHOUR-720*NMONTH-24*NDAY
      WRITE(6,7) NMONTH,NDAY,NHOUR
      WRITE(6,56) IFLAG
   56 FORMAT(1X,'VAPOUR/LIQUID  1 OR 9 - HERE IS =',I1)
      WRITE(6,114) IDELTA
  114 FORMAT (1X,'TIME BETWEEN RECORDINGS=',I10)
      WRITE (6,12)BETAI,BETAE
   12 FORMAT (1X,'BETAI AND BETAE ',2E10.2)
      WRITE(6,203)TXI,TXE
  203 FORMAT(1X,'SURFACE TEMPERATURES ' ,2F10.1)
      WRITE(6,10)PI,PE,WI,WE
   10 FORMAT(1X,'INSIDE AND OUTSIDE AIR',2E9.2,2F8.1)
      WRITE(6,8) (W1(K),K=1,M)
      GO TO 28
  105 CONTINUE
      IF(IFLAG.LE.8) GO TO 107
      IF(NTIME.GT.IBB) GO TO 106
      GO TO 26
  106 CONTINUE
      IF(IFLAG.EQ.9) GO TO 108
      IF(NTIME.LT.MMTIME) GO TO 60
      IDELTA=IDRY
      NEWS=2
      GO TO 60
  109 CONTINUE
      ITURN=ITURN+1
      IAA=86400*IRDAY(ITURN)
      IF(ITURN.GT.LL) IAA=SLUT
      CORRW=1.0
      IFLAG=1
      FLUXI=-EPS
      WLIM=AWMIN
      NUMBER=1
      LOOP=1
      WTURN=AWMAX
      IF(AK2.GT.CRITW) WTURN=AK2
      IF(AK2.GT.CAPW) WTURN=CAPW
      CORRZ=DELTAW/(WTURN-AWMIN)
      WSTART=AK2
      JST=IFIX(WSTART/IN)
      DSTART=D(JST)
      BETAE=BDRYE
      BETAI=BDRYI
      ABC=ZSURF+1.0/BETAI
      BETAI=1.0/ABC
      ZRAND=DSTART/DCAPW
      IF(ZRAND.LT.1.0) ZRAND=1.0
      IF(ZRAND.GT.2.0) ZRAND=2.0
      IF(DSTART.GT.DCAPW) DSTART=DCAPW
      ZBETA=BETAI*ZRAND
      BETAI=ZBETA
      DH=DHWET
      ER=DH/DX
      EA=ER/DX
      DO 401 K=1,M
      JL(K)=1
      W2(K)=WP(K)
      W1(K)=IFIX(W2(K))
  401 CONTINUE
      LTIME=NTIME+7200
      GO TO 30
  107 CONTINUE
      IAA=NTIME
      IF(ITURN.GT.LL) IRTIME(ITURN)=86400
      IBB=IAA+IRTIME(ITURN)
      IBC=NTIME
      TIME=NTIME
      IFLAG=9
      FLUXI=SEPS
      LOOP=1
      CORRW=DELTAW/(CRITW-AWMIN)
      DH=DHWET
      ER=DH/DX
      EA=ER/DX
      IDELTA=IDWET
      BETAI=BWETI
      BETAE=BWETE
      CVI=100.0
      PI=0.0
      N=W(NC)
      WI=FLOAT(N)
      DO 400 K=1,M
      JL(K)=1
      W1(K)=IFIX(W2(K))
  400 CONTINUE
      GO TO 26
  108 CONTINUE
      IBC=NTIME+DH
      TIME=NTIME+DH
      MMTIME=NTIME+18000
      NEWS=1
      GO TO 109
  100 CONTINUE
   19 FORMAT(10I10)
      IK=IKMAX/10
      DO 67 I=1,IK
      MM=10*I
      N=MM-9
      WRITE(6,19) (KAL(IJK),IJK=N,MM)
      WRITE(6,19) (KAB(IJK),IJK=N,MM)
   67 CONTINUE
      STOP
      END
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DEFINITIONS.

The following list is based on the Glossary of Soil Science Society of America, Statement of the Review Panel in the Symposium on Engineering Concepts of Moisture Equilibria and Moisture Changes in Soils (1965) and the Research Program of Adamson, Ahlgren, Bergström & Nevander published in Swedish (Adamson et al., 1970).

Pore water - Water contained in the porous material. It is understood to be the equilibrium solution in the material; pure water refers to the chemically pure compound H_2O.

Moisture content - The amount of water lost from the material upon drying to the absolute dryness, expressed as the mass of water per unit of the total volume of the material i.e. in kg/m^3.

Moisture ratio - The ratio of the volume of water in a material to the total volume of the material.

Moisture weight percentage - The moisture content expressed as a percentage of the absolute dry weight of the material.

Absolute dryness - The state of the material dried at 378 K or under equivalent conditions until the material reaches a constant weight.

Saturate - To form the most concentrated solution possible under a given set of physical conditions in the presence of an excess of the solute.

Absolute saturation - Maximal possible moisture content of the material. (In practice this is obtained with the help of temperature or vacuum.)

Degree of saturation - The ratio between the actual moisture content and the absolute saturation of the material.

Degree of actual saturation - The ratio between the actual moisture content and the maximum moisture content when the actual drying run was started.

Capillary saturation - Moisture content at the knick point on the diagram of moisture content versus logarithm of time (or square root of time) under specified conditions of the free water intake test. (Se

Gravitational potential - The amount of work that must be done per unit quantity of pure water in order to transport reversibly and isothermally an infinitesimal quantity of water, identical in composition to the pore water, from a pool at a specified elevation and at atmospheric pressure, to a similar pool at the elevation of the point under consideration.

Capillary potential - The amount of work that must be done per unit quantity of pure water in order to transport reversibly and isothermally an infinitesimal quantity of water, identical in composition to the pore water, from a pool at the elevation and the external gas pressure of the point under consideration, to the pore water.

Gas pressure potential (pneumatic potential) - This potential component is to be considered only when external gas pressure differs from atmospheric pressure differs from atmospheric pressure as, e.g., in a presure membrane apparatus. A specific term and definition is not given.

Envelope - pressure potential (overburden potential) - is a potential component when the external pressure is introduced on the porous body containing the pore water.

Pore water pressure - The pressure (positive or negative), relative to the external gas pressure on the pore water, to which a solution identical in composition to the pore water must be subjected in order to be in equilibrium through a porous permeable wall with the pore water. May be identified with the capillary potential defined above.

Total pressure - The pressure (positive or negative), relative to the external gas pressure on the pore water, to which a pool of pure water must be subjected in order to be in equilibrium through a semipermeable membrane with the pore water. Total pressure is thus equal to the sum of pore water pressure and osmotic pressure. Total pressure may also be derived from the measurement of the partial pressure of the water vapor in equilibrium with the pore water.May be identified with the total potential defined above when gravitational and external gas pressure potentials can be neglected.

Capillary water - (obsolete). The water held in the "capillary" or pores of a material, usually with a suction less then 6×10^2 Pa.

Hygroscopic water - Water held by the material when it is in equilibrium with an atmosphere of a specified relative humidity at a specified temperature, usually 98 % RH at 20 to 25 °C.

Darcy's law as formulated by Darcy the law is:

$$Q = k \cdot S \left(\frac{H + e}{e}\right)$$

where

Q is the volume of water passed in unit time
S is the area of the bed
e is the thickness of the bed,
H is the height of the water on top of the bed, and
"k is the coefficient depending on the nature of the sand" and for cases where the pressure "under the filter is equal to the weight of the atmosphere".

Darcy's law (generalisation). The rate of viscous flow of homogeneous fluids through isotropic porous media is proportional to, and in the direction of, the driving force

Total potential (of pore water) - The amount of work that must be done per unit quantity of pure water in order to transport reversibly and isothermally an infinitesimal quantity of water from a pool of pure water, at a specified elevation and at atmospheric pressure, to the pore water (at the point under consideration). The total potential consists of the following:

Osmotic potential - The amount of work that must be done per unit per unit quantity of pure water in order to transport reversibly and isothermally an infinitesimal quantity of water from a pool of pure water, at a specified elevation and at atmospheric pressure, to a pool of water identical in composition to the pore water (at the point under consideration), but in all other respects being identical to the reference pool.

Hydraulic head - The elevation with respect to a specified reference level at which water stands in a piezometer connected to the point in question in the material. Its definition can be extended to material above the water table if the piezometer is replaced by tensiometer. The hydraulic head in systems under atmospheric pressure may be identified with a potential expressed in terms of the height of a water column. More specifically it can be identified with the sum of gravitational and capillary potentials, and may be termed the hydraulic potential.

Total suction - The negative gauge pressure relative to the external gas pressure on the pore water to which a pool of pure water must be subjected in order to be in equilibrium through a semi-permeable membrane with the pore water. Total suction is thus equal to the sum of matrix or pore water suction and osmotic suction. Total suction may also be derived from the measurement of the partial pressure of the water vapour in equilibrium with the pore water.

It should be noted that this quantity may be identified with the total potential defined above when gravitational and external gas pressure potentials can be neglected.

Matrix or capillary suction - The negative gauge pressure relative to the external gas pressure on the pore water, to which a solution identical in composition with the pore water must be subjected in order to be in equilibrium through a porous permeable wall with the pore water.

It should be noted that this quantity may be identified with the matrix or capillary potential defined above.

Osmotic (or solute) suction - The negative gauge pressure to which a pool of pure water must be subjected in order to be in equilibrium through a semi-permeable (i.e. permeable to water molecules only) membrane with a pool containing a solution identical in composition with the pore water.

It should be noted that this quantity may be identical with the osmotic potential defined above.

Moisture conductivity (Hydraulic conductivity) - The proportionality factor in Darcy´s law as applied to the viscous flow of water in porous media. Note that it may be assumed constand in the saturated flow and dependent on moisture content in the unsaturated flow.

Moisture diffusivity - The proportionality factor between the flux of moisture(density of the moisture flow rate) and the gradient of moisture content in the absence of other force fields.

Moisture-retention curve - A graph showing the moisture content of the material versus applied suction (pore water pressure, or tension). Points on the graph are usually obtained by increasing (or decreasing) the applied pressure over a specified range. We distinguish between the utmost drying (desorption) retention curve when the pressure is raised from the equilibrium at the absolute saturation and the utmost wetting (absorption) retention curve when the pressure is lowered from the equilibria at the aboslute dryness. See absolute saturation, absolute dryness and moisture content.

Differential moisture capacity - The absolute value of the rate of change of moisture content with the pore water pressure (suction). The moisture capacity at a given moisture content will depend on the particular desorption or adsorption curve employed.

Permeability - The case with which gases or liquids penetrate or pass through the porous material. Previously, frequently considered the "k" in Darcy´s law.

Intrinsic permeability - The property of a porous material that relates to the case with which gases or liquids can pass through it. The Darcy "k" mulitiplied by $\eta/\rho g$ where:

η is the viscosity of the fluid
ρ is the density of the fluid, and
g is the acceleration of gravity.

Vapour permeability - The proportionality factor between the flux of moisture and the partial vapour pressure gradient in the absence of liquid phase transport.

Bubbling point - The highest moisture content obtained during a given drying run when the corrected capillary suction is equal to the capillary suction.

Note that for different drying processes, various values of the bubbling point may be obtained.

Bubbling pressure (Air entry value) - The pressure of pore-water being in equilibrium at the bubbling point.

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